Digitized by the Internet Archive
in 2013

http://archive.org/details/researchpaper35inte

PUBLIC DOCUMENTS
DEPOSITORY ITEM
SEP 2 9 1989
CLEMSON
LIBRARY

A 13.78:INT-359

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station
Ogden, UT 84401**

Research Paper
INT-359

February 1986

Modeling Moisture Content of Fine Dead Wildland Fuels:

Input to the BEHAVE Fire Prediction System

**Richard C. Rothermel
Ralph A. Wilson, Jr.
Glen A. Morris
Stephen S. Sackett**

CLEMSON UNIVERSITY
AUG 29 1986
PUBLIC DOCUMENTS

THE AUTHORS

RICHARD C. ROTHERMEL received his bachelor of science degree in aeronautical engineering from the University of Washington in 1953 and his master's degree in mechanical engineering from Colorado State University, Fort Collins, in 1971. He served in the U.S. Air Force as special weapons aircraft development officer from 1953 to 1955. Upon his discharge he was employed at Douglas Aircraft Co. as a designer and trouble shooter in the armament group. From 1957 to 1961 Rothermel was employed by the General Electric Co. in the aircraft nuclear propulsion department at the National Reactor Testing Station in Idaho. In 1961 he joined the Intermountain Fire Sciences Laboratory, Missoula, MT, where he has been engaged in research on the mechanisms of fire spread. He was project leader of the fire fundamentals research work unit from 1966 until 1979 and is currently project leader of the fire behavior research work unit at the fire sciences laboratory.

RALPH A. WILSON, JR. is a research physicist assigned to the fire behavior research work unit at the Intermountain Fire Sciences Laboratory, Missoula, MT. His undergraduate studies were at Willamette University, Salem, OR (B.A. 1956), with graduate work from 1956 to 1960 at University of Oregon (M.A. 1958). He worked in infrared detectors and optics at Naval Ordnance Test Station, China Lake, CA, from 1957 to 1964. He worked with the Forest Service's airborne infrared forest fire surveillance project at Intermountain Fire Sciences Laboratory, 1964 to 1975.

GLEN A. MORRIS holds a bachelor's degree in mathematical statistics from the University of Washington and a master of science degree in mathematics from the University of Wisconsin. His function has been programming and mathematics in connection with aircraft structures at the Boeing Company and navigation systems at AC Electronics in Milwaukee, WI. He came to the Forest Service in Missoula, MT, in 1970 to provide similar support to research on lightning and forest fires and is at present providing that support for the fire behavior research work unit.

STEPHEN S. SACKETT is a research forester (fire) stationed at the Forestry Sciences Laboratory in Flagstaff, AZ. He is a research scientist with the fire effects portion of the Management of Southwestern Forests and Woodlands research work unit of the Rocky Mountain Forest and Range Experiment Station. Sackett received an associate of science degree in forestry at Olympic Junior College, Bremerton, WA, in 1958, and a B.S. degree in agricultural economics in 1962 and an M.S. degree in forest economics in 1964 from the University of Wisconsin. He joined the staff at the Southern Forest Fire Laboratory in 1964 with the fire use research work unit. Sackett transferred to the Forestry Sciences Laboratory in Tempe, AZ, in 1974 with the forest fuels research project of the Rocky Mountain Forest and Range Experiment Station. In 1984, Sackett was relocated to Flagstaff, AZ, to continue his research in prescribed fire effects in southwestern ponderosa pine forests.

RESEARCH SUMMARY

A method for predicting the time-dependent nature of fine fuel moisture is badly needed to support fire behavior prediction systems used in fire management. Of the models available, none met all the requirements of the BEHAVE fire behavior prediction system. The Canadian Fine Fuel Moisture Code (FFMC) came closest to meeting our needs and was selected as a base model. Improvements to the FFMC were concentrated on providing a means of accounting for annual and diurnal variation due to solar heating of woody fuels. This was necessary because the FFMC was developed for fuels located within forest stands, a generally shaded condition. Solar heating raises the temperature of the fuel surface and lowers the relative humidity of the film of air surrounding the fuel particle. Formulas describing this near-fuel environment produce the temperature and relative humidity that are then used by FFMC to derive the moisture content. The solar intensity that drives the fuel temperature and relative humidity accounts for latitude, time of year, time of day, aspect, slope, elevation, atmospheric haze, and shade. Shade can be from clouds or overstory trees. Provisions are made to guide the user through tree descriptors necessary to determine expected amount of shade.

Basic operation of the model will determine fine fuel moisture for early afternoon. Provisions are made for extending the prediction over the next 24 hours (day or night) by use of a diurnal code developed in Canada and adapted for this model. It uses prediction of weather conditions at sunset and sunrise to extend the model capabilities throughout the diurnal cycle.

The model was tested against actual moisture data taken from general fuel types in Texas, Arizona, Idaho, and Alaska. It consistently proved to be a better predictor of moisture than currently operating procedures.

ACKNOWLEDGMENTS

We appreciate the efforts of the many individuals who contributed to this diverse manuscript. Collecting field data on a regular basis over long periods is a tedious task. Fortunately, we found a rich source of data among scientists scattered over the west: Rod Norum (Alaska), Bob Clark and Henry Wright (Texas), Mick Harrington (Arizona), and Bill Frandsen and Larry Bradshaw (Idaho).

We also thank Al Simard and Bill Main for the computer program of the Canadian Fine Fuel Moisture Code, and Marty Alexander for the latest references to Canadian publications.

Finally, thanks to Charlie Van Wagner for his friendly consultation.

CONTENTS

	Page
Introduction	1
Review and Discussion	1
Objectives	3
Model Logic and Equations	4
Initialization	5
Elevation Correction	7
Solar Heating	7
Shade	14
Fuel Level Windspeed	19
Canadian Standard Daily Fine Fuel Moisture Code (FFMC)	21
Canadian Hourly Fine Fuel Moisture Code	21
Diurnal Predictions	21
Validation	24
Purpose of Validation	24
Daily Version Validation (Objective No. 1)	25
Initialization Validation (Objective No. 2)	31
Validation of Diurnal Capability (Objective No. 3)	32
References	38
Nomenclature	42
List of Equations	44
Appendix A: Canadian Standard Daily Fine Fuel Moisture Code (FFMC)	46
Explanation	46
Appendix B: Canadian Hourly Fine Fuel Moisture Code	47
Appendix C: Correction for Initial Shade Conditions in FFMC	48
Appendix D: Sunrise and Sunset Determination	48
Appendix E: Methods of Estimation for Missing Model Inputs	49
Internal Estimation of H_2, H_3, ..., H_N and Other Humidities	50
Internal Estimation of T_2, T_3, ..., T_{N-1}	50
Internal Estimation of M_o	50
External Estimation of Missing Inputs	51
Appendix F: Formula Used for Humidity and Dew Point Calculations	51
Appendix G: Summary of Validation Data	52

Modeling Moisture Content of Fine Dead Wildland Fuels: Input to the BEHAVE Fire Prediction System

Richard C. Rothermel
Ralph A. Wilson, Jr.
Glen A. Morris
Stephen S. Sackett

INTRODUCTION

The model described here was developed to predict fuel moisture content of fine fuels for use with the BEHAVE fire behavior prediction and fuel modeling system. BEHAVE is a computer system designed to aid fire managers and field personnel to assess fire situations and carry out operational planning (Andrews 1986; Burgan and Rothermel 1984). BEHAVE requires a model that will predict fine fuel moisture over a wide variety of conditions. We had planned to predict fine fuel moisture with the procedures developed for use by fire behavior officers (FBO's), described by Rothermel (1983); however, BEHAVE will be used over a wider range of conditions than the relatively dry situations encountered by FBO's on escaped fires. Consequently, a more robust model is needed. A review by Simard and Main (1982) of the available moisture models identified the Canadian Fine Fuel Moisture Code as the best choice. To use it throughout the wide range of conditions found in this country, however, required modifications and additions. The major change was the method of accounting for drying of surface fuels by solar radiation. Other changes include a new method of initiating the model at any time of the season without a complete record of weather data prior to the startup time, and a method for integrating the daily code with a diurnal code for estimating fine fuel moisture at any time of the day or night.

REVIEW AND DISCUSSION

Fine fuel moisture is one of the primary factors controlling the behavior of wildland fires (Barrows 1951). Methods for predicting it have been sought for many years by those seeking means for rating fire behavior (Van Wagner 1974; Fosberg and Deeming 1971; Deeming and others 1972; Luke and McArthur 1978; Rothermel 1983). Various methods have been under scrutiny for some time. Simard and Main (1982) recently published a comprehensive comparison of moisture prediction systems. Their analysis, based on fine fuels and litter from jack pine logging slash in Minnesota, concluded that:

> Predictions from the Canadian Forest Fire Weather Index (FWI) models and some meteorological elements were superior to the National Fire Danger Rating System (NFDRS) models for every fuel tested. It appears that the FWI models are well suited to moist climates, whereas the NFDRS models work better under dry conditions.

In fairness, it should be pointed out that the NFDRS system is intended to indicate the worst-case condition, and Simard and Main's data did not include the 10-hour stick moisture measurement. This is an important element in the NFDRS system to account for seasonal changes.

CLEMSON UNIVERSITY LIBRARY

Because the FBO procedures (Rothermel 1983) are based in part on the NFDRS models, and because users of BEHAVE will not usually have 10-hour stick moisture data available, we decided to evaluate the Canadian Fine Fuel Moisture Code for use with BEHAVE.

The Fine Fuel Moisture Code (FFMC) is a component of the Canadian Forest Fire Weather Index System (Canadian Forestry Service 1984). The literature is rich with descriptors of the Canadian Fire Weather Index and the moisture codes. We will not attempt to summarize it all here. Van Wagner (1974) describes the evolution of the index:

> The FFMC was developed from concurrent weather and fuel moisture data obtained in pine stands at Petawawa, Ontario, by multiple correlation of present moisture content with current weather and previous day's moisture content. Although pine needles are relatively fast drying, they found that there was a substantial effect of the previous day's moisture content which meant that drying cannot be assumed to be instantaneous. Thus, the method of estimating fuel moisture is based on a known or previous value and adjustment to it according to weather during the intervening 24 hours. The rate of change is commensurate with atmospheric conditions imposed upon the fuel and the final equilibrium value. This code calculates a daily value of fine fuel moisture for the afternoon.

The idea of yesterday's fuel moisture content affecting today's fine fuel moisture content may be hard to accept by those trained to equate fine fuels with 1-hour time lags. However, recent information shows that some conifer needles have time lags as long as 30 hours (Anderson 1985). These fuels will not come close to equilibrium in a typical 24-hour diurnal cycle.

Because the FFMC was developed from data taken beneath a canopy of jack pine trees, it cannot adequately account for drying of fuels exposed to the sun; a condition important to the fuels in a large part of the world.

The effects of solar radiation on fuel moisture and fire hazard were recognized early in the present century (for example, Plummer 1912). Gast and Stickel (1929) found that "diminution in the radiation intensity incident upon the duff reduces the rate at which the duff moisture content decreases during the day," and further suggested ". . . the importance of a cloud 'weather eye' to patrolmen. By estimating cloudiness, the probable hazard can be estimated."

Gisborne (1928) gives data for exposures to different totals of radiation and concludes that determining changes in moisture is of value only when the amount of shielding from sunlight is varied. Gisborne (1933) hypothesized a mechanism of wind and solar radiation to account for observations of dead wood lying on the ground being drier than in air. Again, Gisborne (1936), explaining the operation of his forest fire danger meter, referenced the work of Hornby (1935) who also emphasized exposure to sun and wind in fuel classification. Byram (1940) reported that his experiment showed excellent evidence that the effects of wind and sunshine on fuel moisture are not additive, but partially compensating; that the energy of sunshine seems to be a very powerful drying agent, and wind prevents some of this energy from being absorbed by the fuels; and, further, that the reflection factor of fuels has considerable effect on their moisture content when exposed to sunlight—black sticks absorbing more than

white, hence having lower moisture contents. Countryman (1977) found moisture variation under a ponderosa pine stand (*Pinus ponderosa* Laws.) to have significant variation within short distances—enough to offset ignition and fire behavior significantly. These variations were found to be caused primarily by solar radiation reaching some litter areas through openings in the crown canopy and cooling directly under the openings at night. Catchpole and Catchpole (1983) found that a large portion of the variation in spread rate of experimental grass fires in Australia (statistical variation between fires) could be attributed to the degree of cloud cover.

In 1943 Byram and Jemison reported on a method they developed whereby radiation intensity could be determined for any season of year, hour of day, slope, and aspect. They established a relationship of solar radiation intensity to surface fuel moisture equilibria and rates of drying. Van Wagner (1969) used Byram and Jemison's model as a basis for investigating the effect of solar heating and wind on the surface temperature of jack pine needles and quaking aspen leaves. He obtained results similar to theirs with a slightly different mathematical form. The solar heating section of our model is an extension and application of Byram and Jemison's original idea.

In the interim many authors have investigated solar irradiance on the terrestrial surface (Kimball 1919; Bates and Henry 1928; Okanoue 1957; Lee 1962; Loewe 1962; Kaufmann and Weatherred 1982; Running and Hungerford 1983).

The correct solar-terrestrial geometry varies among authors only in detail. Our customers will be oriented to local standard time; to measuring slope aspect clockwise from north; to measuring slope angle positive (up) in the sense opposite the slope aspect . . . etc.

We wish also to circumvent the popular concept of "equivalent slope" because of the geometric difficulties encountered when the shade trees are standing at tilted slant angles on that "equivalent horizontal slope." (See, for example, Okanoue, Lee, Kaufmann and Weatherred.)

OBJECTIVES

Our objectives in developing a new model are to predict the moisture of fine dead fuels with greater accuracy over a wider range of conditions and times than possible with the FBO procedures (Rothermel 1983). The main concerns with the FBO system are its inability to account for precipitation prior to the day of the fire and its tendency in northern latitudes to underestimate moisture values of fuels beneath a forest canopy.

Simard and Main suggest at least five characteristics of a fuel and its environment that must be specified when developing a predictive model:

1. Composition of the material (wood, needles, leaves, grass).
2. Presence of surface layer (bark, wax).
3. Thickness (diameter of wood).
4. Location (on, off the ground).
5. Environment (under a canopy, in the open).

A summary of the characteristics to be accounted for by this model is given below:

1. The model will be applicable to fine dead fuels, needles, leaves, cured herbaceous plants, and dead stems less than one-fourth inch in diameter.
2. The model should be sensitive to atmospheric moisture. This is the most common factor in all models wherein an equilibrium fuel moisture is determined based on air temperature and humidity and the fuel moisture is continually seeking this equilibrium value. (The influence of soil moisture on fuel moisture, perhaps through dew formation, is an important consideration for future revisions to this model.)
3. The model should be sensitive to the drying effect of solar radiation. This requires a considerable amount of additional information. The amount of solar heating depends upon day length, sun angle, windspeed, and shade. These, in turn, depend upon time of year, latitude, slope, aspect, cloud cover, and overstory conditions.
4. The model should be sensitive to precipitation occurring within 7 days preceding the fire.
5. The model should be capable of predicting fuel moisture any time of the day or night.
6. The model should be capable of accounting for elevation differences by adjusting temperature and humidity to fire locations above or below the position where they are measured.
7. Inputs must be available to a knowledgeable person without requiring a previously assembled weather data file.
8. Because the fuel moisture is intended for use in a fire behavior model (Rothermel 1972; Albini 1976), wherein fires are in fuels with moistures less than a specified moisture of extinction (usually less than 30 percent), attention will be concentrated on accuracy at the lower levels.
9. The model should account for atmospheric haze.

Considerations omitted at this time are:

1. Differences in moisture because fuels are either standing (such as grass) or lying on the ground.
2. Differences between freshly fallen and old litter.
3. Differences caused by fuel coating, such as bark or wax.
4. The effect of dew.
5. The effect of moisture in the duff and soil beneath the litter layer.

The reasons for omitting these influences at this time are threefold: (1) We do not have the necessary information to model the process; (2) every new model requires data from the user when applying the model, and it is not clear how some of these data would be known to the user; and (3) a necessity to derive a solution in a reasonable time, with a strong expectation that the planned improvements will make the model significantly better than present methods.

MODEL LOGIC AND EQUATIONS

A simplified model flow diagram is shown in figure 1. There are six major sections to the model:

1. Initialization (accounting for previous weather).
2. Current situation (time, site description, weather forecast).
3. Correction for elevation.
4. Correction for solar heating (adjusting air temperature and relative humidity to fuel level).

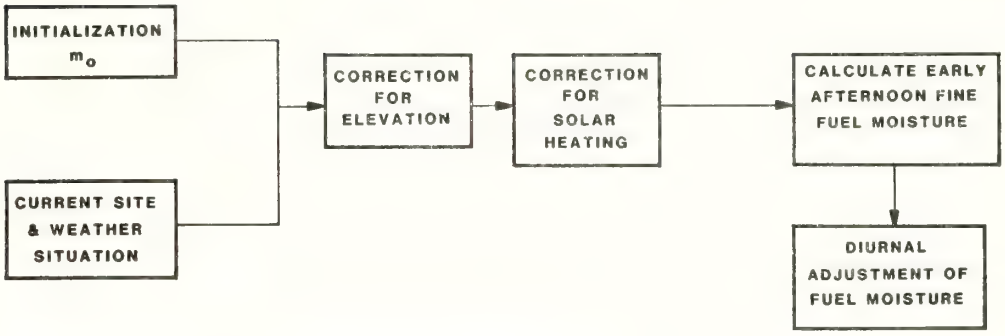


Figure 1.—Flow diagram of fine fuel moisture model.

5. Calculation of early afternoon fine fuel moisture.
6. Diurnal adjustment of fuel moisture.

Briefly, the model shown in figure 1 is used as follows. It must be initiated by one of five options that appraise the weather for 3 to 7 days preceding the day on which a prediction is wanted. This is necessary to establish a reference moisture value for the day preceding the day on which a prediction is wanted. The five options are designed to accommodate the type of information the user might know about preceding weather events.

The inputs describe the prediction day weather and site conditions. The elevation correction is designed to adjust the air temperature and humidity[1] from the elevation where they were measured to the elevation where the moisture content is wanted. If the fuel is exposed to the sun, a correction is made to predict the fuel surface temperature and the air moisture condition in immediate proximity to the fuel. The effect of turbulent mixing caused by wind at the fuel level is included. The adjusted temperature and humidity will determine the effect of atmospheric moisture on the fuel. These values are entered into the Canadian Fine Fuel Moisture Code, which then calculates the early afternoon fine fuel moisture.

If moisture is needed at another time, additional data are requested from the user and the early afternoon moisture is used as a starting value for advancing fuel moisture through to the time that a prediction is needed (projection time), which must not be later than 1200 of the next day.

Details of the model components follow.

Initialization

The model requires a value for the 1400-hour fuel moisture for the day preceding the day for which you wish to make a prediction. This value is called the initial fuel moisture (m_o) and the process of determining it is called initialization. Five options are provided for obtaining m_o:

1. m_o is known.
2. Weather records are available for several preceding days.
3. Complete weather data are not available and it rained within the past week.
4. It has not rained within the past week and weather conditions have been persistent from day to day.

[1]The term humidity is sometimes used rather than relative humidity; in this publication, humidity always means relative humidity.

5. It has not rained within the past week and weather conditions have been variable.

These options do not exhaust all ways of initiating the model. As the user becomes familiar with the initialization process, it will be seen that these options can be adapted to needs and climates. For instance, option 3 may work very well even if there were no rain at the beginning of the period.

Option 1 - m_o is known.—If the previous day's early afternoon fine fuel moisture is known from measurement or a previous calculation or an estimate, it may be used directly.[2]

Option 2 - weather records available.—If the standard NFDR early afternoon fire weather measurements are available for 3 to 7 preceding days, the following data are entered for early afternoon of each day:

air temperature
relative humidity
amount of rain
20-foot windspeed
percent cloud cover

The 1400-hour moisture for the first day of the series is obtained by iterating the first day's weather data with the sun-adjusted FFMC until an equilibrium solution is reached. Then the data from each subsequent day are used as per the normal procedures of the Canadian system. The final value of moisture calculated in this initialization process is used as m_o. This tedious option can be avoided by most users. It is included for those who wish to be exact or test the system.

Option 3 - complete weather data not available, and rain occurred.—If it has rained within the past week and if there has been no frontal passage since it rained, this option may be used.

Rain can act as a triggering event, causing a major change in fine fuel moisture. The occurrence of rain is a logical choice for initiating a new moisture prediction. The occurrence of rain is also unique enough that a fire manager could be expected to know or be able to find out when the last rainfall occurred and be able to estimate how much. The assumption of no frontal passage is necessary to make calculations about the air mass between the time of rain and projection time.

Enter:

(1) How many days since it rained (2 to 7).
(2) Amount of rain, inches.
(3) The early afternoon temperature on the day it rained.
(4) What has been the sky condition on the days since it rained?
    (a) clear
    (b) cloudy
    (c) partly cloudy.

---

[2]If the NFDR 10-hour stick moisture is known, Simard (personal communication) has shown that fine fuel moisture can be calculated from the formula $m = -8.74 + 2.90\ (10\text{-h})$. This correlation was made in the Lake States; it is not known how well it works elsewhere.

These will give cloud cover values of 10, 90, and 50 percent, respectively.

(5) Today's (fuel moisture projection day) complete weather data (measured or forecast).

On the day it rained, the model assumes humidity = 90 percent, cloud cover = 90 percent, and windspeed = 5 mi/h if these values are not known. Early afternoon temperature and humidity on the days since it rained are reconstructed as follows: temperature is adjusted linearly between the day it rained and today. Today's dewpoint is calculated from today's temperature and humidity. Using the assumption of constant air mass since it rained, the humidity on each day is calculated from today's dewpoint and the linearly estimated temperature for each day. (See appendix F for humidity calculation from dew point.)

When fuel moisture on the day before it rained is unknown, it is set to equilibrium for conditions on the day it rained. Any error will be overcome by the rain and successive calculations.

Option 4 - no rain within the past week and weather persistent.—Under these conditions, the fine fuel moisture will also persist from day to day. Today's early afternoon weather is iterated to find an equilibrium value.

Option 5 - no data available and weather during the preceding week has been variable.—Here, none of the preceding four situations can be utilized, but an estimate can be made as follows:

(1) Estimate yesterday's early afternoon weather conditions.

(2) What was the general weather pattern before yesterday?

(a) hot and dry

(b) cool and wet

(c) between (a) and (b).

These will give initial fuel moisture values of 6, 76, and 16 percent respectively. These rough estimates will be adjusted twice, once by yesterday's estimated weather and once by today's measured or forecasted weather.

Elevation Correction

It is often impossible or impractical to measure the weather at the site where the fuel moisture estimate is needed. In mountainous terrain, the temperature and moisture of the atmosphere change with elevation. For a well-mixed atmosphere, the adiabatic lapse rate is used to adjust temperature and humidity according to elevation differences. The correction amounts to 3.5 °F per 1,000 feet for temperature and 1.1 °F per 1,000 feet for the dewpoint. Both corrections decrease with elevation. This correction has been used by others dealing with mountain meteorology (Running and Hungerford 1983).

The corrections should only be applied when there is good mixing, such as in the late morning and afternoon when inversions have broken, and at night if neither location lies within an inversion.

If elevation differences are small, say less than 1,000 feet, the correction is ignored.

Solar Heating

Many fuels in the United States, particularly rangelands in the West and Southwest, are exposed to considerable solar heating. We wanted the moisture model for BEHAVE to be able to account for this, but not to underpredict

moisture, as the FBO model often does, in northern latitudes under a forest canopy.

The physical basis of the problem is that, while some of the sun's energy is absorbed by the air, the solid fuel particles absorb heat more efficiently and consequently the fuel temperature can rise to a much higher temperature than the air temperature, which is measured 4½ feet above the surface in a shaded weather shelter (fig. 2). Furthermore, the warmer fuel temperature alters the microclimate near the fuel on the ground, particularly the humidity of the air surrounding the fuel. The relative humidity of the air adjacent to the fuel particles heated by the sun will be lower than the relative humidity in the instrument shelter. The overall effect is a lower fuel moisture than what would be calculated from the shelter measurements.

Figure 2.—Environmental conditions influencing fuels subject to solar heating are not measured by instruments in weather shelter.

Wind sweeping over the fuel confounds the problem. The moving air above the fuel will be cooler than the thin layer of air surrounding the fuel particles. Consequently, any turbulent mixing will tend to cool the air near the fuel, bringing it closer to the general air temperature and humidity.

A solution began with the research on solar heating by Byram and Jemison (1943). They attacked the problem directly by constructing and using a weather synthesizer or artificial sun to determine the effect of solar intensity and windspeed upon fuel temperature and moisture. From heat transfer considerations explained in the original text, Byram and Jemison developed an equation to be evaluated with data from the artificial sun apparatus. The difference in temperature between the air and the fuel is assumed to be directly proportional to the incident radiation intensity, I, and inversely proportional to the wind velocity, U, and two constants attributed to fuel conditions.

$$T_f - T_a = I/(0.015U_{h'} + 0.026), \quad (1)$$

where

T_f = temperature of fuel, °F,
T_a = temperature of air, °F,
I = radiation intensity, cal/cm^2 • min,
$U_{h'}$ = wind velocity at fuel level, mi/h.

The units are preserved from the original text. From Byram and Jemison's experimental data, the constants were evaluated to be 0.015 and 0.026, respectively. They emphasized that in fuel types in which loss of heat to the soil underlying the litter and loss to the air proceed at faster or slower rates than in the beds of hardwood leaf litter used in their investigation, other values would be needed in place of their constants.

We agree, and after reviewing our verification data believe that these factors should be investigated in the next revision to this type of model.

Using vapor pressure arguments concerning the air temperature and moisture immediately adjacent to the fuel, Byram and Jemison develop a correction for relative humidity as a function of the fuel temperature and air temperature:

$$H_f = H_a \exp(-0.033(T_f - T_a)), \quad (2)$$

where H and T refer to humidity and temperature, and the subscripts f and a refer to fuel and air.

Equations 1 and 2 provide the means to adjust the air temperature and humidity to the fuel level and thus account for solar heating and wind cooling effects. To do this, however, we must have a means of determining the solar radiation intensity I as a function of the solar terrain slope geometry, and windspeed at the fuel level.

Solar/Terrain Slope Geometry.—The development of the basic equations for the solar irradiance on a horizontal surface neglecting the atmosphere is lost in antiquity (Milankovetch 1930; Frank and Lee 1966; Kaufmann and Weatherred 1982 . . .).

Using the particular construction of Byram and Jemison (fig. 3)

$$I = (I_a/r^2) \sin A, \quad (3)$$

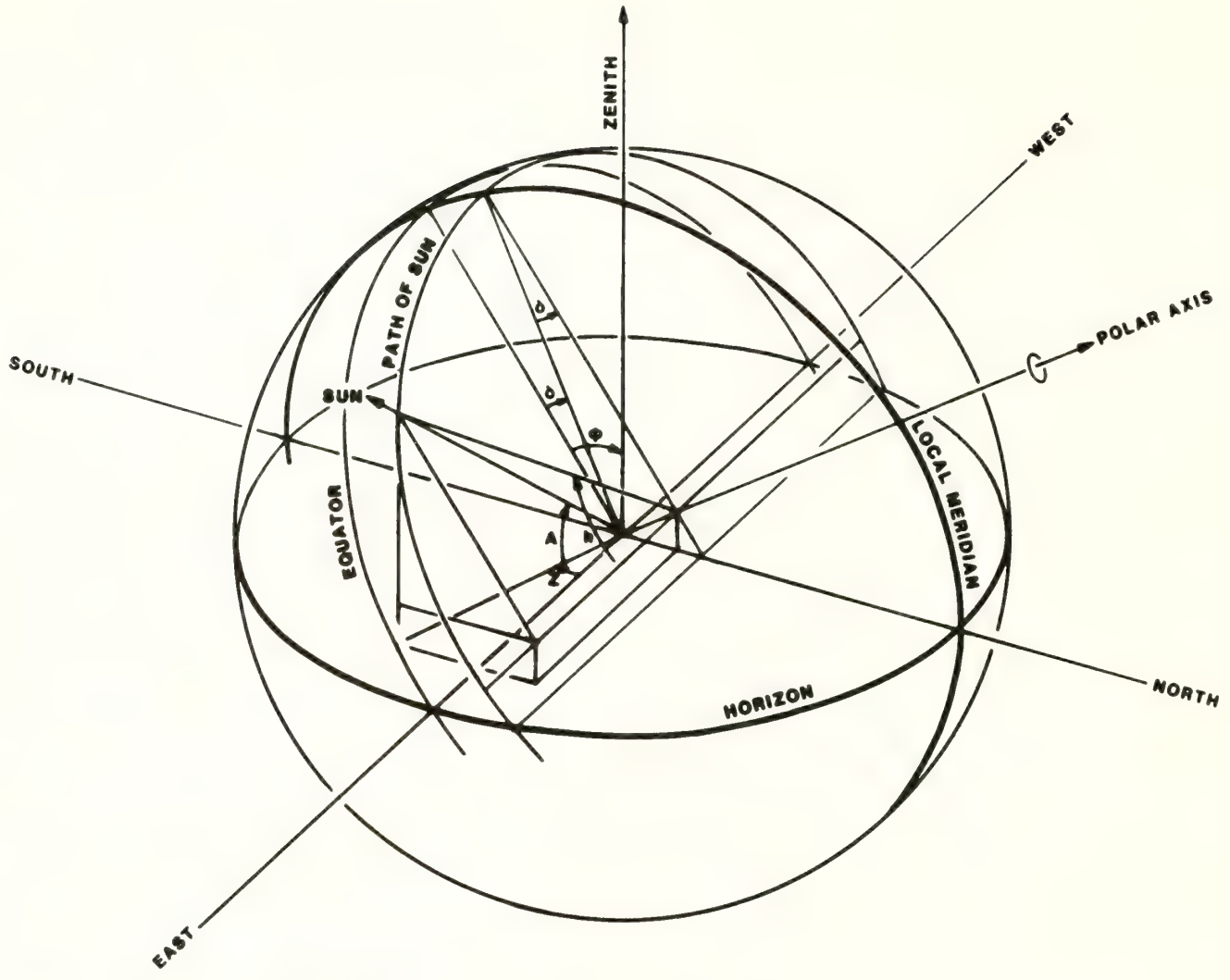


Figure 3.—Diagram of solar geometry.

where I_a is irradiance at the earth's surface, perpendicular to the solar rays, and attenuated by intervening atmosphere, clouds, timber canopy, etc. The earth-sun (center of mass) distance, r, in units of its mean value varies from 0.98324 (January 3) to 1.01671 (July 5) (see List 1958, table 169); thus r^2 varies less than $\pm 3\frac{1}{2}$ percent annually and may be neglected as having a much smaller effect on the solar intensity than unpredictable atmospheric absorption, for example. The solar altitude angle, A, is given by

$$\sin A = \sin h^* \cos \delta \cos \phi + \sin \delta \sin \phi, \quad (4)$$

where

h^* = hour angle from the local 6 a.m.,[3]
ϕ = latitude,
δ = solar declination.

Because the inverse trigonometric functions are double valued in the complete cycle, 0 to 2π, and because computer software does not return angular values in a consistent half cycle, we provide a redundant calculation of the solar azimuth

[3]i.e., the hour angle, $h^* = (360/24)(t - 6.0)$, where t is scaled in fractions of hours and, for example, t = 13.5 represents 1330 military or 1:30 p.m. civil time.

to remove the double value ambiguity. (There is no ambiguity in the solar elevation angle, A, if it is understood that $-\pi/2 \leq A \leq \pi/2$. There are situations, however, where the solar azimuth must range the full 2π circle.)

Thus, from figure 3,

$$\tan z = \frac{\sin h^* \cos \delta \sin \phi - \sin \delta \cos \phi}{\cos h^* \cos \delta}, \text{ and} \tag{5}$$

$$\cos z = \cos h^* \cos \delta / \cos A. \tag{6}$$

By simple ratios of equations 5 and 6, any function of solar azimuth, z, may be calculated over the full range $0 \leq z \leq 2\pi$.

Kaufmann and Weatherred (1982) give the analytic solution to List's tabular values of r and δ:

$$r^2 = 0.999847 + 0.001406\,(\delta),$$

$$\delta = 23.5 \sin(0.9863(284 + N_J))$$
$$= \text{solar declination in degrees,} \tag{7}$$

$$N_J = \text{Julian date}$$
$$= \text{Integer Value } (31(M_o - 1) + D_y - 0.4M_o - 1.8 + \epsilon) \tag{8}$$

$$\epsilon = \begin{cases} 2 \text{ if } M_o = 1, \\ 3 \text{ if } M_o = 2, \\ 1 \text{ if } M_o > 2 \text{ on leap years,} \\ 0 \text{ otherwise.} \end{cases}$$

M_o and D_y are the month and day, respectively, of the Gregorian calendar and Integer Value means round up or down to nearest integer.

Irradiance on a slope (neglecting the small variation in r) is

$$I = I_a \sin \zeta, \tag{9}$$

where angle A in equation 3 is replaced by ζ, the solar angle to the slope in the plane normal to the slope (fig. 4) and

$$\sin \zeta = \sin (A - \psi) (\cos \alpha)/\cos \psi, \tag{10}$$

where $(A - \psi)$ is the solar angle to the slope in the local vertical plane and ψ is the slope angle at the solar azimuth, z,

$$\tan \psi = \tan \alpha \sin(z - \beta) \tag{11}$$

and angles A and z are determined from equations 4 and 5 (with equation 6 where necessary), respectively. Note from figure 3 that the nodes of sin A (eq. 4) determine sunrise and sunset and that $I = 0$ for $\sin A < 0$. Note also that, for proper choice of slope and aspect (for example, $\beta = 0$ and $\alpha > \delta$, a steep north slope) one may observe two "sunrises" and "sunsets" on the slope.

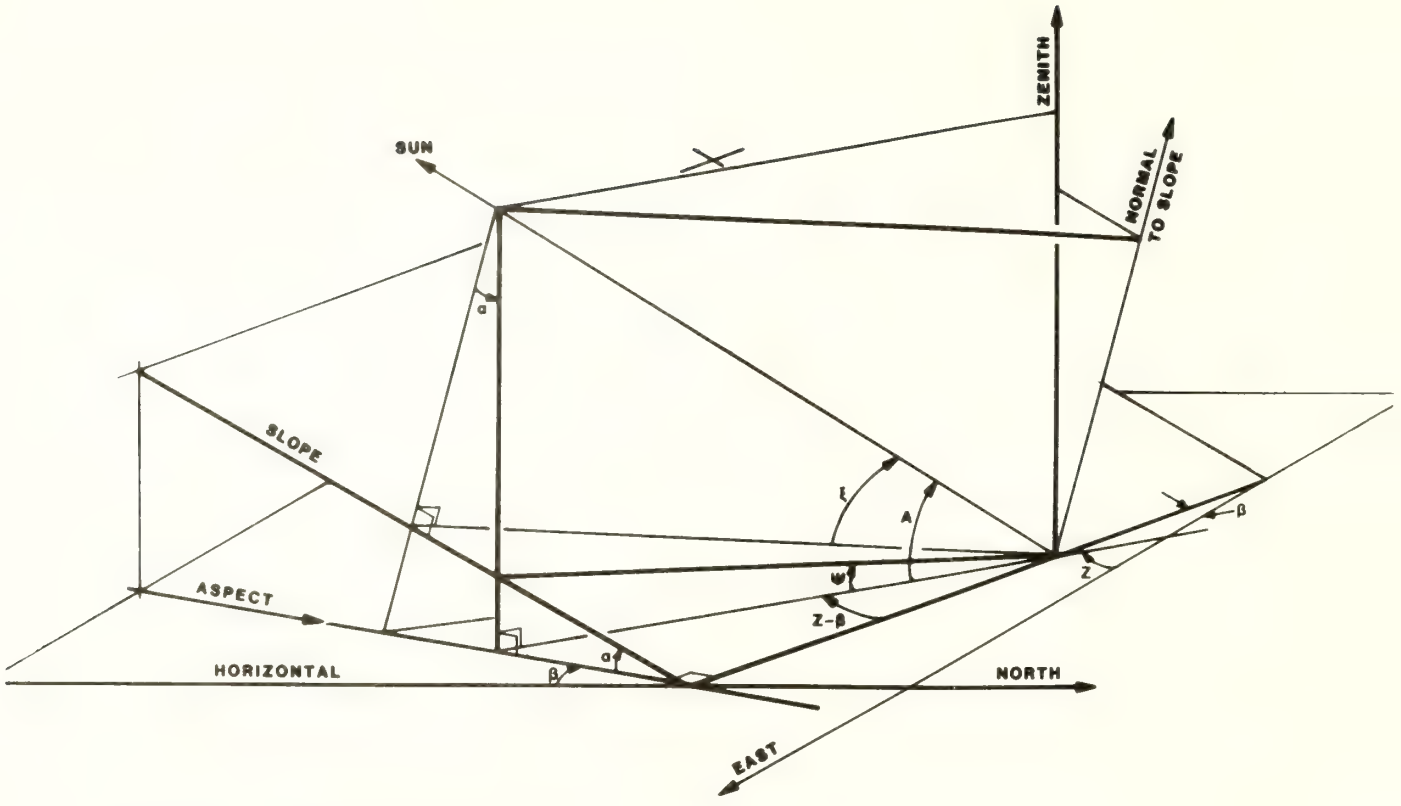


Figure 4.—Diagram of sun/slope geometry.

Obscuration and Attenuation of Irradiance.—The irradiance, I_a, of equation 9, on the forest floor is the product of the incident solar power density and the transmittance of the intervening media:

$$I_a = I_M \tau_n, \tag{12}$$

where τ_n is the net transmittance of clouds and trees discussed below, and I_M is the direct solar irradiance including atmospheric attenuation.

The direct solar irradiance, I_M, may be written (see Kondratyev 1969, ch. 5, or Johnson 1960, ch. 4):

$$I_M = I_o p^M, \tag{13}$$

where I_o is the incident intensity or solar constant, 1.98 cal/cm^2•min (variously quoted as I_o = 1.84 to 1.98 cal/cm^2•min).

p is the transparency coefficient (integral over all wavelengths).

M, the optical air mass, is the ratio of the optical path length, l_M, of radiation through the atmosphere at angle, A, to the path length, l_{zo}, toward the zenith from sea level. Thus

$$M = l_M/l_{zo} = l_z \text{ (csc A)}/l_{zo}. \tag{14}$$

The air mass M is referenced to the optical path l_{zo} at **sea level**. If one is working at a few thousand feet elevation, the zenith air mass optical path, l_z, is significantly reduced (at 5 km elevation you are above half of the air mass!):

$$l_z = l_{zo}\ \varrho/\varrho_o\ , \tag{15}$$

where ϱ is the absolute atmospheric pressure at the site and ϱ_o is the sea level pressure (1,000 mb). For an elevation, E, in feet above sea level, ϱ is approximately

$$\varrho = \varrho_o \exp\ (-0.0000448E).$$

Thus,

$$M = (\varrho/\varrho_o)\ \csc\ A = \exp(-0.0000448E)\ \csc\ A, \text{ and} \tag{16}$$

$$I_a = I_o \tau_n p^M. \tag{17}$$

Because of the earth's curvature, optical refraction by the air density gradient, etc., the exact csc A dependence of solar irradiance on solar altitude angle fails near the horizon, that is, for A < 10 degrees. But because the irradiation just after sunrise and before sunset is "small" and the probability of shading is very high, we will let the approximation stand for those small angles.

Atmospheric transparency, p, is most notably dependent on absorption of radiation by differing amounts of atmospheric moisture and by atmospheric turbidity (haze). Even an empirical estimation of p requires knowledge (radiosonde measurement) of the vertical distribution of temperature, pressure, and relative humidity in addition to measures of dust-haze and particulates. Acquisition of such data is beyond the scope of the BEHAVE system. It is sufficient to say that Byram and Jemison used a constant p = 0.7, which they assumed was a "reasonable average for a thin layer of rather dense haze which is common at 2,000 feet during the fire season in the southern Appalachians," and that a 30-year mean value at Pavlovsk, Russia (Kondratyev 1969) was p = 0.745, with extreme values of 0.710 (1914) and 0.770 (1909) and a typical annual (12-month) variation of $\Delta p = \pm 0.02$ (except for the 2-year period following the eruption of Katmai volcano (Alaska) in 1912 when the annual average transparency was 0.57). Similar data are presented in the other monographs on atmospheric transparency. The mean Kondratyev value represents a "clean forest atmosphere." On exceptionally clear days p may range as large as 0.8 and on very hazy days as small as 0.6, excluding direct interference from local smoke palls. The list below suggests a series of p values with qualitative descriptors for application by field observers.

p	**Qualitative description**
0.8	exceptionally clear atmosphere
0.75	average clear forest atmosphere
0.7	moderate forest (blue) haze
0.6	dense haze

Shade

The net cloud/tree transmittance from above is

$$\tau_n = \tau_c \cdot \tau_t, \quad (18)$$

where τ_t is the transmittance of the timber canopy and $\tau_c = (1 - S_c/100)$ is the transmittance of cloud cover. S_c is scaled in percent.

Cloud Shade.—Cloud shade is familiar to users of the National Fire-Danger Rating System as a contribution to the state of the weather code. For this model the user can enter any percentage of cloud cover between 0 and 100. When working with the NFDRS state of weather code, convert to percent cloud cover according to the following:

NFDRS code	Shade range	Input
	Pct	*Pct*
0	0 - 10	5
1	10 - 50	30
2	50 - 90	70
3	90 - 100	95

Tree Shade.—Many authors have suggested that the Beer-Lambert exponential absorption model of solar radiation is applicable to forest plant communities and that the Leaf Area Index (LAI) may be the significant attenuation parameter (Monsi and Saeki 1953; Jordan 1969; Barbour and others 1980).

Considerable work has been done to relate site productivity, habitat classification, and topographic distributions to LAI (see also Stage 1976; Pfister and others 1977; Zavitkovski 1976; Salomon and others 1976). Those relationships have not been satisfactorily established nor has LAI become a universally established mensurational parameter, so that we can use it in the present application. Instead, our site-specific approach to shade is an extension of the method suggested by Satterlund (1983). In the Satterlund approach the shadow area of an average tree on a unit surface area is calculated, then the fractional area of shadow cast by n trees is estimated. Because the tree crowns are not totally opaque we assume a Beer law attenuation and estimate the optical attenuation coefficient on the basis of shade tolerance and crown shape.

We consider crowns of two general geometric shapes (fig. 5). Conifers are right circular cones; deciduous trees are assumed to be ellipsoids of revolution. The tree boles are totally opaque with a vertical cross section approximated by an inverted paraboloid of revolution.

For a conifer tree (fig. 6A), we require the shadow area, A_h, projected on a horizontal reference plane by the sun at solar altitude, A, crown diameter, D, and length, L. (The unsubscripted A is the solar altitude angle while A with subscripts is a shadow area on the ground.) We have two cases:

$$A_h = \pi D^2/4, \text{ for conifers, if } \tan A \geq 2L/D, \text{ or} \quad (19)$$

$$A_h = (\pi - G)D^2/4 + DL \cot A \sin G, \text{ if } \tan A < 2L/D \quad (20)$$

where

$$\cos G = (2\,(L/D) \cot A)^{-1}. \quad (21)$$

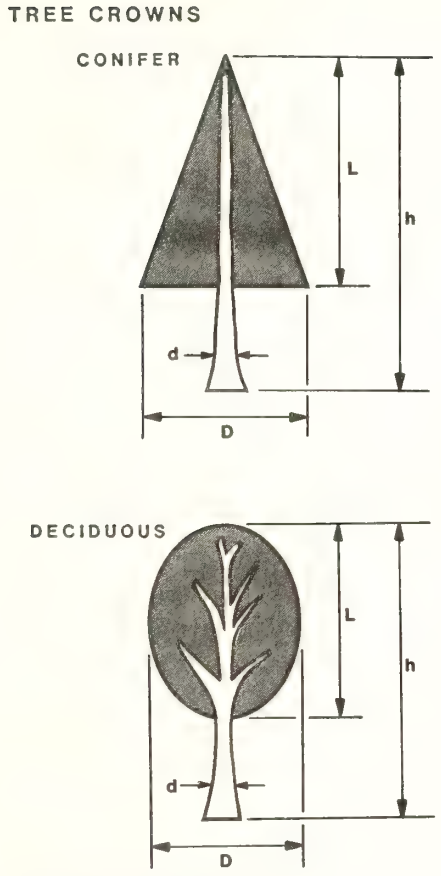


Figure 5.—Tree crown shape assumptions.

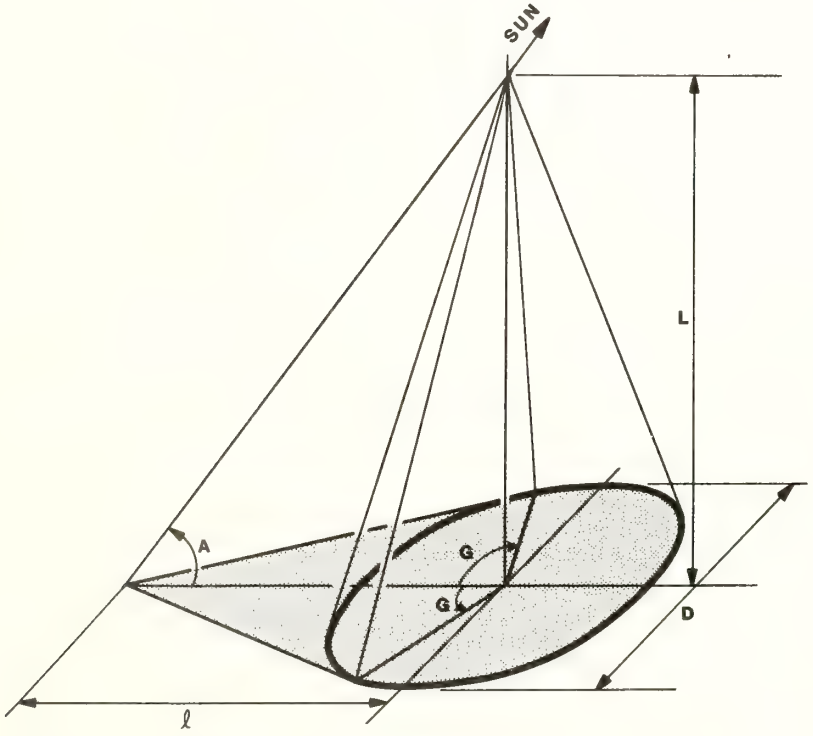


Figure 6A.—Conifer tree shadow configuration.

For deciduous trees (fig. 6B) with crown dimensions of L/2 and D/2 semi-axes, the height-to-width ratio is L/D and A_h is

$$A_h = \pi D l/(2 \sin A) \text{ for deciduous,} \quad (22)$$

where

$$l = r' \sin(G' - A), \quad (23)$$

$$\tan G' = -(L/D) \cot A, \text{ and} \quad (24)$$

$$r' = (L/2)(\sin^2 G' + (L/D)^2 \cos^2 G')^{-1/2}. \quad (25)$$

Because the crowns are not opaque we assume an exponential attenuation function, exp(−JX), where the optical attenuation coefficients, J ft^{-1}, exclusive of the opaque tree boles, are estimated below from data on file at IFSL (USDA FS 1968). (In deciduous forests shade tolerance for present purposes may equal zero.)

Crown type	Shade tolerance class			
	0	1	2	3
Conifer	NA	0.13	0.16	0.20
Deciduous	0	0.10	0.12	0.20

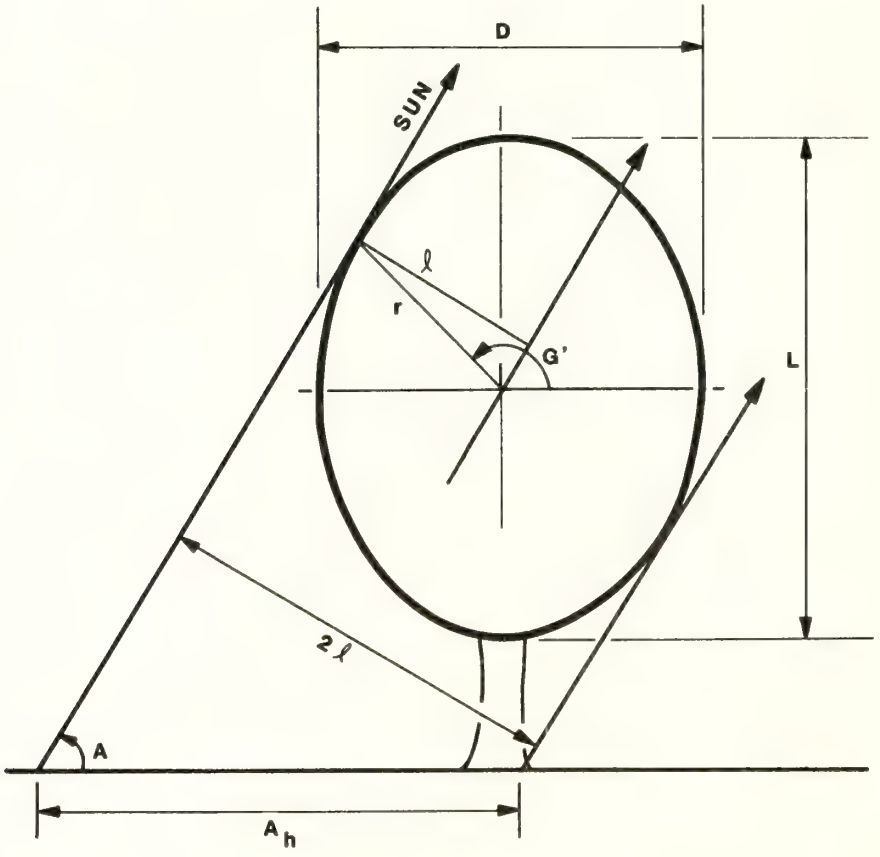


Figure 6B.—Deciduous tree shadow configuration.

The intracrown path length, X (fig. 6C), is approximated:

$$X = V/(A_h \sin a) \quad --$$

$$= \pi D^2 L/(12\ A_h \sin A) \text{ for conifers} \quad (26)$$

$$= \pi D^2 L/(6\ A_h \sin A) \text{ for deciduous} \quad (27)$$

If one adds the shadow of a parabolic tree bole of height h and diameter d (vertical cross section area 2/3 dh), the horizontal bole shadow A_b cast is

$$A_b = (2/3)\ dh \cot A \quad (28)$$

In the model we use the approximation d/h = 0.014 (ft/ft), then

$A_b = 0.0093\ h^2 \cot A$. The net "effective" tree shadow on the horizontal is

$$A_h' = A_b + A_h\ (1 - \exp(-JX)) \quad (29)$$

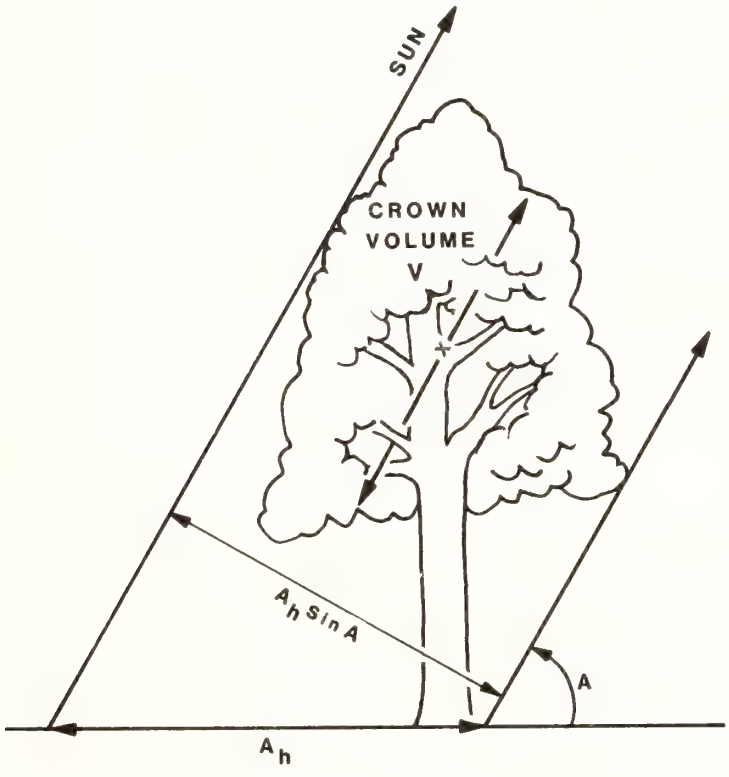


Figure 6C.—Intercrown path length relationship.

For either tree type, the area A_h is the shadow projected to a horizontal reference plane. The shadow, however, is actually cast on the slope, S (fig. 6D), and the vertical projection of S onto a horizontal plane, A_s, is

$$A_s = A_h'(\cos \psi \sin A)/ \sin(A + \psi) \quad (30)$$

The fractional area N_1 shaded by one average tree per unit horizontal surface area, A_u (usually ha or acres), is

$$N_1 = A_s/A_u. \quad (31)$$

Then, assuming that the trees are independently distributed, the shadow of the n^{th} tree is expected to add to the total shaded area an amount equal to the product of its relative shadow area, N_1, and the unshaded area, $(1 - N_{n-1})$ by $n-1$ trees such that:

$$N_2 = N_1 (1 - N_1) + N_1,$$
$$N_3 = N_1 (1 - N_2) + N_2,$$
$$N_n = N_1 (1 - N_{n-1}) + N_{n-1}, \text{ or}$$
$$N_n \cong 1 - \exp(-nN_1), \quad (32)$$

where N_n is the area shaded by n trees and

$$\tau_t = 1 - N_n = \exp(-nN_1) \quad (33)$$

approximates the expected fraction of direct beam solar radiation impinging on the moist fuel under the timber canopy in equation 18.

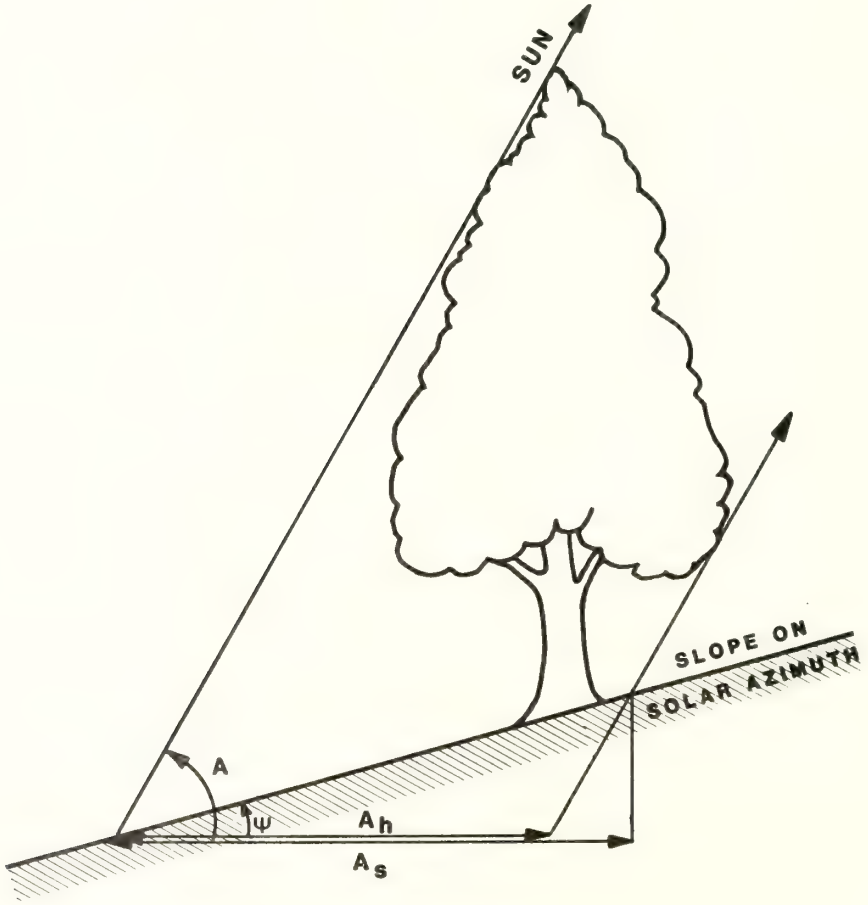


Figure 6D.—Shadow relationship to slope.

An alternative estimate of the number of trees per unit area, n, that is consistent with this rationale is as follows: Given the crown closure, C, and average tree diameter, D, then the vertically projected crown area, A_s', of one tree is

$$A_s' = \pi D^2/4$$
$$N_1' = A_s'/A_u .$$

By definition, then

$$N_s' = C = 1 - \exp(-nN_1') \quad (34)$$
$$n = -ln(1 - C)/N_1'$$
$$n = -4A_u\, ln(1 - C)/\pi D^2 \quad (35)$$

One must caution that A_s' **is not** the proper **effective** crown area, A_s, used in equation 31. A_s' is the total area within the crown perimeter while calculations of A_s (in eq. 31) must include the transparency of the particular crown type as developed above.

A list of the equations and pertinent constants is given at the end of the text.

Fuel Level Windspeed

Byram and Jemison's equation for calculation of surface fuel temperature (eq. 1) requires a value for the windspeed at the fuel surface. This is not a trivial correction; even though windspeeds close to the surface are low, Byram and Jemison's data show that the cooling effect can be pronounced.

The standard height for measuring windspeed for fire applications in the United States is 20 feet above vegetation height (Fischer and Hardy 1976). Many authors have described how surface roughness reduces wind near the ground as shown in figure 7. Albini and Baughman (1979) developed a relationship that includes vegetation height, making it easy to adapt to fire situations. Their ratio of windspeed at vegetation height to that at 20 feet above the vegetation is given by:

$$U_{h'}/U_{20+h'} = 1/ln((20 + 0.36h')/0.13h') \quad (36)$$

where

$U_{h'}$ = windspeed at vegetation height,
$U_{20+h'}$ = windspeed at 20 feet above vegetation,
h' = vegetation height.

Equation 36 gives reasonable answers as shown by the examples below:

h'	$U_{h'}/U_{20+h'}$
0.1	0.0006
.5	.17
1.0	.2
6.0	.3

For exposed conditions, the vegetation height windspeed is determined by multiplying the windspeed measured 20 feet above the vegetation by the ratio in equation 36. For unexposed (sheltered) conditions, a fraction called the wind adjustment factor is input to the model instead of the fuel depth. The wind adjustment factor times the canopy-top wind estimates a reduced wind near the fuel.

For daytime application of the model, the only inputs required are the 20-foot windspeed and the fuel bed depth or wind adjustment factor. In the BEHAVE application fuel bed depth is already known from the fuel model and guides for determining the wind adjustment factor are given.

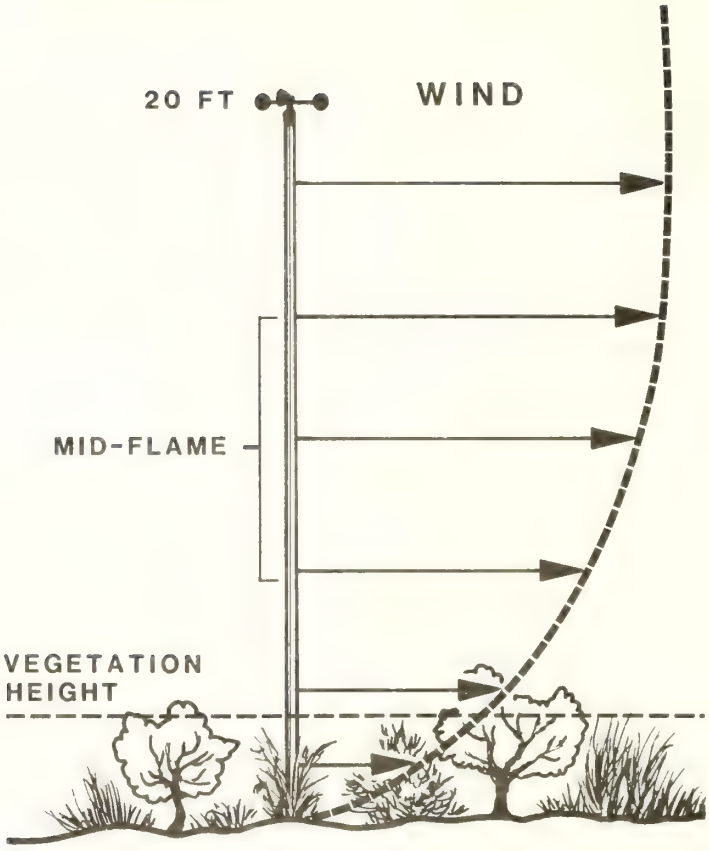


Figure 7.—Near-surface wind profile.

For nighttime application in uneven terrain, downslope winds may need to be considered. Slope winds do not follow the log reduction pattern used in daytime. At night, if the slope is less than 5 percent, use the daylight procedures. If the slope is greater than 5 percent, and if the 20-foot windspeed is less than 10 mi/h, let the vegetation height wind equal 4 mi/h (a reasonable assumption for downslope winds). If the windspeed is greater than 10 mi/h, consider the canopy closure; if the closure is less than 10 percent, use the daylight procedures. If the canopy closure is greater than 10 percent, assume the 20-foot winds are blocked and let the vegetation height wind equal 4 mi/h.

The effect of wind on fine fuel moisture is also incorporated directly in the Canadian Fine Fuel Moisture Code. Van Wagner (1974) explains that wind affects the log drying rate, k,

$$k = a + b\,(U_{20})^{0.5} \tag{37}$$

where U_{20} is the windspeed at 20 feet.

Consequently, windspeed in the Canadian code is directly related to the **rate** at which fuel moisture approaches equilibrium.

The two wind corrections (eqs. 36 and 37) use windspeed measured at different heights. The fine fuel moisture code was calibrated to winds measured at the international standard height, 10 meters, in the open. The solar heating correction requires windspeed at the vegetation height. The U.S. standard established for NFDR stations is 20 feet. The ratio of windspeed at 10 m to 20 feet (6.1 m) can be calculated from equation 36 if the vegetation height is known. We assume the windspeed at 20 feet and 10 meters are the same in this model.

Canadian Standard Daily Fine Fuel Moisture Code (FFMC)

The FFMC accepts initial fuel moisture, temperature, humidity, wind, and rain as inputs. In our model, the FFMC is used to calculate fine fuel moisture after the inputs are adjusted for elevation and solar heating. The version used in our model is the same as used by Simard and Main (1982). Like any large system, the FFMC has undergone many revisions. Work on the FFMC subsequent to the version we used is designed to provide consistency for table presentation and to give better moisture predictions under very wet conditions, 100 to 250 percent. It is not expected that these changes would affect our model significantly. The formulations of the FFMC we used are given in appendix A.

Canadian Hourly Fine Fuel Moisture Code

The other major condition to be accounted for by this model is the capability to make a calculation of expected moisture content at any time of the day or night. As presently used, the Canadian standard daily FFMC is structured to give a moisture value for midafternoon with data collected at noon, local standard time. Fortunately, the Canadian Forestry Service has also investigated diurnal prediction. Muraro and others (1969) used litter data sampled from a dry lodgepole pine site near Prince George, BC, to produce tables for adjusting the FFMC for various times of the day or night. Van Wagner (1972) developed a new scale supplemented with data from a jack pine forest at Petawawa, and produced a single table for predicting FFMC based on time, initial FFMC, and relative humidity.

Van Wagner (1977) developed a set of equations, similar to the standard daily FFMC, that would accept hourly weather data, thereby freeing the model from the restraint of the original data and a single value of humidity. Alexander and others (1984) programmed the equations so that hourly computations of the FFMC and other components of the Canadian Forest Fire Weather Index system could be made on a handheld calculator with weather measured or forecast hourly. The BEHAVE model, as will be shown, adds the capability of predicting the necessary weather elements over a 24-hour period.

Diurnal Predictions

Unfortunately, weather forecasts on an hourly basis for extended periods are not readily available. It was necessary, therefore, to devise a way of estimating hourly weather from a few forecasts at key times. This is done by initiating the diurnal predictions from the daily moisture prediction and weather data at 1400 hours. This is supplemented with a forecast at the time when the prediction is needed and with estimates of weather data at sunset and sunrise if projection time is after sunset or sunrise. Temperature and relative humidity values at each hour are predicted from sinusoidal curves linking the 1400 weather to the projection time weather. No trend for wind or cloud cover can be justified, so linear interpolations are used. The model will not apply to days with precipitation after 1200 (noon). The model determines hourly values of the weather data needed and performs the adjustments for solar heating. If the user does not have a weather forecast, he/she can estimate the temperature at any of the key points and if the air mass has not changed, the model will estimate the humidity. This will be based on the dew point of the air at the last known condition (calculation shown in appendix).

Beyond noon, the process will begin with a new 1400 fuel moisture calculated by the daily code. A discontinuity in a smooth-line moisture trend can occur between late morning predictions made by the morning code and early afternoon predictions made by the daily code.

Curves used to match weather conditions during each period of the day are described below.

Early afternoon.—If the moisture is needed between 1200 and 1600, the daily value is sufficient and no adjustments are necessary. Personal discussions with Van Wagner confirm this view.

Late afternoon.—In late afternoon, in addition to the 1400 weather, the user must supply a weather forecast at the projection time. The temperature and humidity are assumed to follow cosine curves as shown in figure 8. If sunset conditions are hotter and drier than 1400, the curves will arc in opposite forms.

From figure 8 the temperature, T, at any time t can be expressed as:

$$T = T_{14} + (T_{14} - T_s)(\cos(90(t - 14)/(t_s - 14)) - 1) \quad (38)$$

where T and t refer to temperature and time, respectively, and the subscripts are 14 = 1400 and s = sunset.

Time of sunset is determined by an algorithm using latitude and date (see appendix D). The user enters a forecasted temperature at the projection time and equation 38 is used to determine a hypothetical temperature at sunset, (T_s), which fixes the end point of the cosine curve. Equation 38 will then be used to calculate temperature for each hour between 1400 and the projection time.

The humidity as shown in figure 8 is treated similarly with the following equation:

$$H = H_{14} + (H_{14} - H_s)(\cos(90(t - 14)/(t_s - 14)) - 1) \quad (39)$$

If solar heating is occurring, the air temperature and humidity are adjusted to the fuel level as described earlier for the daily computation.

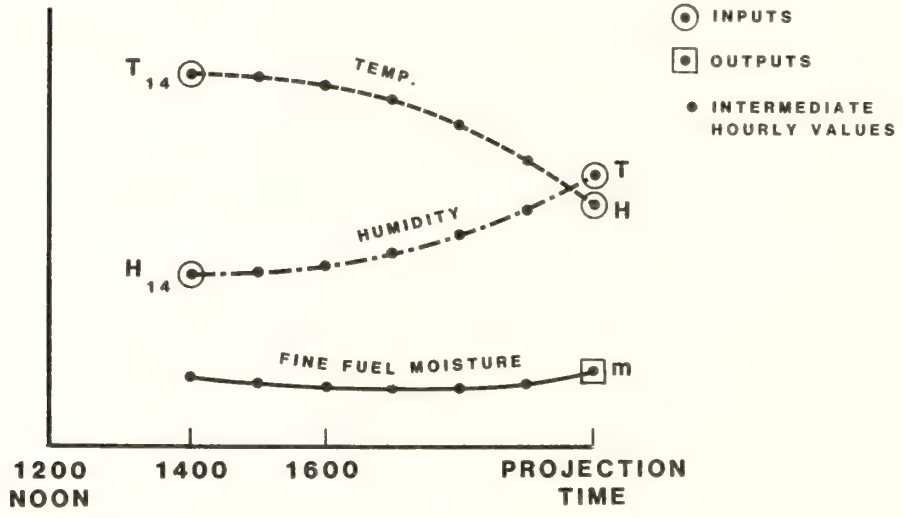


Figure 8.—Typical late afternoon weather and moisture relationships.

Nighttime.—For nighttime, in addition to the 1400 weather data, the user must supply weather conditions at sunset and at the projection time.

The afternoon equations and the diurnal code are used to advance fuel moisture to sunset. Beyond sunset a new set of sinusoidal curves is used to describe temperature and humidity. No corrections for radiation cooling are made; consequently, cloud cover at night is not needed at this time. (Corrections for cooling due to nighttime radiation losses and dew formation should be considered for an update to this model if greater accuracy is needed for the morning.) Windspeed is assumed to vary linearly between sunset and projection time.

Temperature is assumed to be represented by another quadrant of the sine curve from sunset to sunrise as shown in figure 9 and expressed as:

$$T = T_s + (T_r - T_s) \sin(90(t - t_s)/(t_r - t_s)) \quad (40)$$

The user enters a forecast temperature at a projection time. This is used first to fix the end point of the sine curve at sunrise and then temperature is calculated at every hour up to projection time.

After sunset, humidity of the air at shelter height is assumed to be the same as humidity in close proximity to the fuel surface.

A sine curve shape between 0 and 90° is assumed to match humidity between sunset and sunrise as shown in figure 9 and expressed as:

$$H = H_s + (H_r - H_s) \sin(90(t - t_s)/(t_r - t_s)) \quad (41)$$

Predicted relative humidities will not be allowed to go beyond 100 percent. Interestingly, the model may have to artificially set sunrise humidity above 100 percent to develop the correct shape of the sinusoidal humidity curve up to projection time.

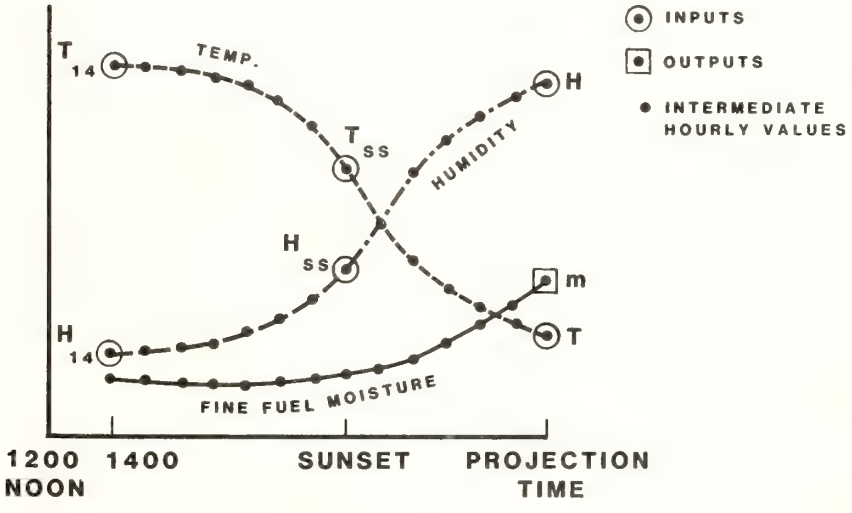


Figure 9.—Typical nighttime weather and moisture relationships.

Morning.—Computations of fuel moisture in the morning, any time between sunrise and 1200 m. (noon), are a continuation of the previous afternoon and nighttime extrapolations. The user must specify weather at 1400 on the preceding day, at sunset of the previous day, and at sunrise on the projection day. A new set of sinusoidal equations is specified for temperature and humidity as shown in figure 10:

$$\text{Temperature, } T = T_{12} + (T_r - T_{12})\cos(90(t - t_r)/(12 - t_r)) \quad (42)$$

$$\text{Humidity, } H = H_r + (H_r - H_{12})(\cos(90(t - t_r)/(12 - t_r)) - 1) \quad (43)$$

Cloud cover and windspeed are extrapolated linearly between sunrise and projection time. The haze level specified at projection time is assumed to be constant from sunrise to the projection time. All solar heating adjustments are made as per the daily code procedures.

The Canadian hourly FFMC used to calculate fuel moisture is very similar to the standard daily FFMC. The equations, inputs, and procedures are given in appendix B.

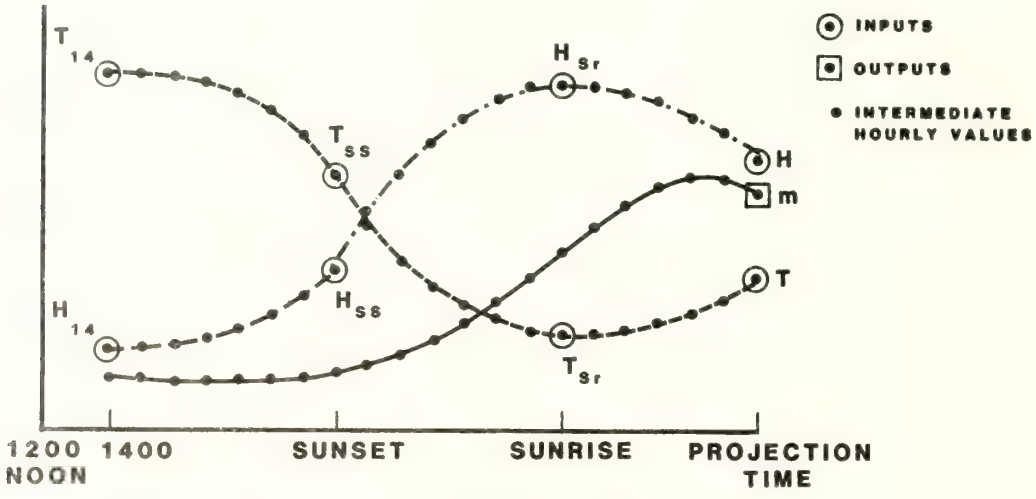


Figure 10.—Typical morning weather and moisture relationships.

VALIDATION

Purpose of Validation

The Canadian FFMC was developed for shaded conditions, while the FBO system patterned after the NFDR system was designed for worst case exposed conditions. This general behavior was confirmed by Simard and Main (1982). The purpose of the validation presented here is to determine if our new moisture model preserves the capabilities of the Canadian FFMC in shaded conditions and improves it significantly in sunny conditions. Similarly, the new model should be at least as good as the FBO methods in dry sunny conditions, and superior in the shade.

Discussion.—The fine fuel moisture model that we have developed is a deterministic model assembled from physical and empirical relationships that expand the capabilities of the Canadian Fine Fuel Moisture Code. The methods of accounting for solar heating, diurnal predictions, and startup in midseason have not been tested. Two separate validation efforts for testing the complete model

were initiated. The first, reported here, uses data already available from several diverse fuel and shade conditions. The second is a study by the University of Montana to test the model independently. Their test will include a sensitivity analysis.

We were fortunate to find a great deal of moisture data with most of the inputs necessary to drive the model. Most of the data were unpublished. We used data from Idaho, Texas, Alaska, and Arizona. The Idaho data were collected at four elevations in conifer litter in the Bitterroot Mountains of Idaho, just south of Missoula (Frandsen and Bradshaw 1980). The Texas data were taken in grass fuels (Clark 1981). The Alaska data were taken in several fuel types and offer a good test of the model at northern latitudes (Norum 1983). Arizona data were taken in open and closed ponderosa pine stands (Harrington 1983; Sackett 1983, 1984). Sackett's data were the only set initiated after model development had been started so that all inputs were specified except haze. Data used in this analysis are shown in appendix G. Input data are in part A; outputs from the models are in part B.

Specific Objectives.—

1. Determine if the daily version of the model can predict fine fuel moisture better than the Canadian Fine Fuel Moisture Code when the fuels are exposed to the sun, and better than the FBO procedures when fuels are heavily shaded.
2. Determine if the initiation procedures that do not use a complete record of preceding weather work as well as those that do.
3. Determine how well the diurnal version of the model can predict fine fuel moisture throughout the diurnal cycle.

Daily Version Validation (Objective No. 1)

Analysis method.—When comparing predictions of models using the same data set, one of two models would probably be superior if it tends to have smaller errors than the other model. Two methods were used to compare the error distributions of the models:

1. Confidence intervals
2. Analysis of variance

The models are unaided by a posteriori correction terms or factors.

The confidence intervals consisted of the following (one unit is 1 percent of ovendry weight, the unit of fuel moisture):

P_1 = percent of predictions falling within 1 unit of the actual fuel moisture

P_3 = percent of predictions falling within 3 units of the actual value

I_{90} = width of a 90 percent confidence interval about the actual value

The best model will have the largest values for P_1 and P_3 and the smallest I_{90}.

Analysis of variance provides a basis for comparing model biases. The procedure gives a significance level (P_F), which gauges the overall repeatability of different subsample means and the relative importance of these means for explaining overall variance. It can be determined if the sample mean error (x) of one model is significantly different from that of another by observing the contrast P-levels produced by the analysis of variance procedure. The data appear to satisfy the premises of analysis of variance reasonably well. Specifically, the contrast P-levels should be meaningful for comparing the BEHAVE and FFMC models in this analysis. The same is true for comparing the BEHAVE and FBO models except for the two hardwood strata, where the variances are no longer equal.

Data and Stratifications.—Data were restricted to measured fuel moistures less than 30 percent, taken between 1200 and 1600. A separate analysis was done for shade conditions less than 30 percent, for 30 to 70 percent, and for greater than 70 percent. This presumes that the amount of shading is largely responsible for variations in fuel moisture. This is a good assumption when one weather station serves three nearby fuel collection sites with different shade, such as was done in Arizona, but is not necessarily true for much of the Alaska data. To meet objective 1, however, we will stratify by shade and presume that heating took place.

One-way analysis of variance was applied to each shade class, the treatment variable being model choice. It is important to note that we cannot test shade effect per se. The low-shade-level data are entirely grass and Arizona pine, while the high-shade data are heavily loaded with northern fuel types. Our approach is to merely perform a model comparison on three separate and interesting subsamples of our data.

Model comparison by means of one-way analysis of variance was also carried out for six fuel types (conifer litter, needles, grass, conifer sticks, hardwood sticks, and leaf litter). Here we cannot test the fuel type effect per se. We merely show that the model comparison does not break down when performed by fuel type.

Results.—Resulting model comparisons are shown in table 1, with highlights plotted in figures 11, 12, and 13.

Whether objective 1 was achieved or not can be judged from figures 11 and 12. In figure 11 the positive bias of the FFMC at low shade values has been eliminated by the additions incorporated in the BEHAVE model. At high shade values, the BEHAVE model and FFMC have the same mean and variance values, whereas the strong negative bias of the FBO model is illustrated.

Table 1.—Statistical summary of early afternoon moisture data comparisons between the three moisture models

Model	Mean error ($\bar{X}$)	Standard deviation (S)	Sample size (N)	Confidence			Contrasts P-level		
				P_1	P_3	I_{90}	1	2	3
				-- *Percent* --			--- *Percent* ---		
Shade <30%									
FFMC	1.96	3.92	28	18	60	±6.2	—	2	1
BEHAVE	-.64	3.93	28	57	81	±5.9	2	—	84
FBO	-.86	3.88	28	47	86	±5.5	1	84	—
							P_F = 0.01, R^2 = 10%		
30 <shade ≤70 %									
FFMC	-1.10	5.33	25	7	45	±10.2	—	58	23
BEHAVE	-1.92	5.04	25	26	52	±9.9	58	—	50
FBO	-2.93	5.39	25	14	52	±13.0	23	50	—
							P_F = 0.46, R^2 = 2%		
Shade >70%									
FFMC	0.40	5.24	170	22	57	±8.1	—	90	0
BEHAVE	.47	5.21	170	22	58	±8.1	90	—	0
FBO	-3.31	5.48	170	21	51	±10.3	0	0	—
							P_F = 0, R^2 = 10%		

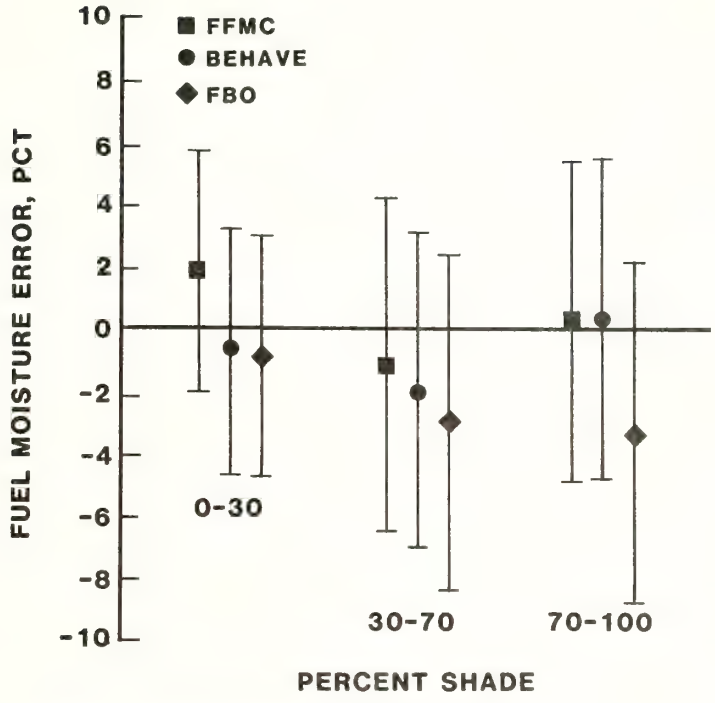


Figure 11.—Early afternoon mean and standard deviation trends for the three moisture models in three shade conditions.

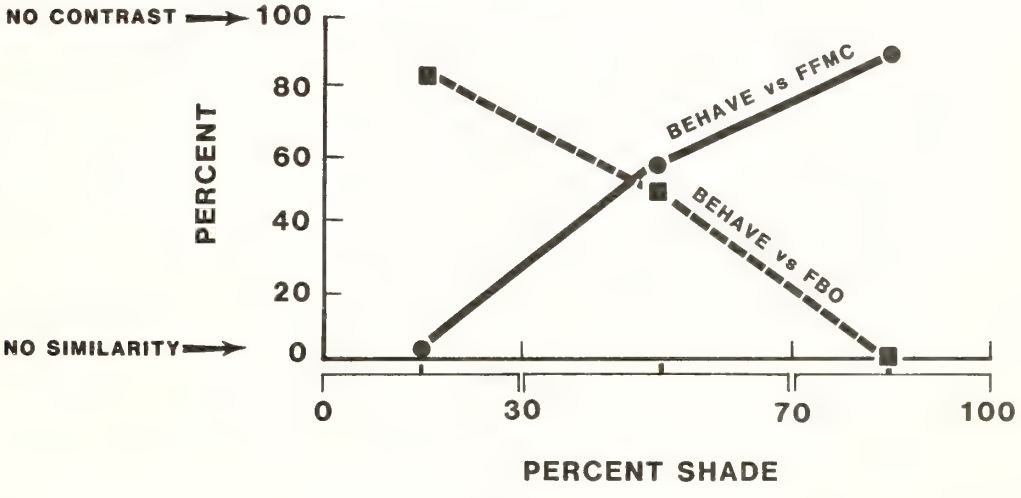


Figure 12.—Contrast P level between BEHAVE and other moisture models.

This is further confirmed in figure 12 where the contrast P level comparing BEHAVE and FFMC increases with shade level. At low shade there is no similarity between the means of the two models, while at high shade they are nearly identical. Contrast between BEHAVE and FBO indicates an inverse trend. At high shade there is no similarity, while at low shade there is very high similarity. Figure 12 is a strong indication that we achieved our first objective.

Actual accuracies are compared by the confidence intervals in table 1. The relative frequency for an error within 1 percent fuel moisture is illustrated with bar graphs in figure 13. At low shade levels, 0 to 30 percent, BEHAVE is within 1 percent of the actual moisture 57 percent of the time, three times better than the FFMC unaided by solar heating corrections. The BEHAVE model, capturing 47 percent of the data within 1 unit of fuel moisture (1 percent), was also better than the FBO model, which worked well.At high shade values, the three models are comparable, with regard to P_1.

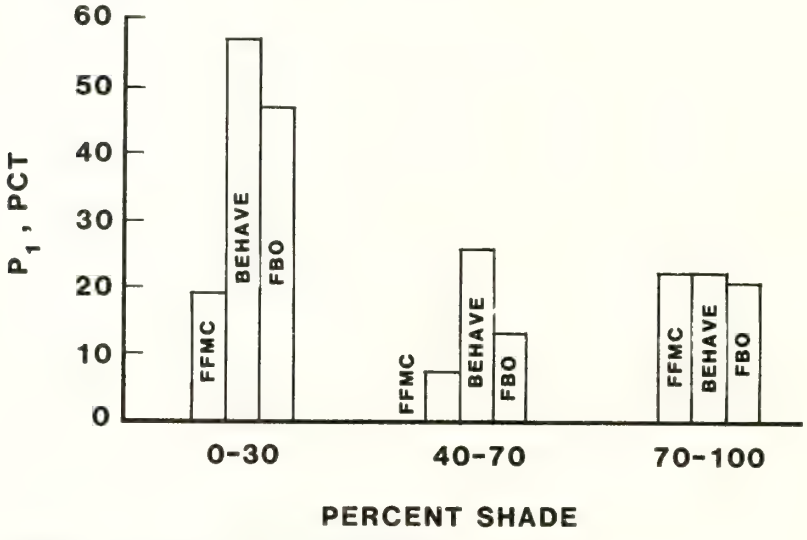


Figure 13.—Errors within 1 percent for the three moisture models in three shade conditions.

At mid-shade levels, 30 to 70 percent, the results are more difficult to interpret. All three models show a negative sample-mean (fig. 11), and there is little contrast between them (fig. 12). BEHAVE does notably better in keeping errors to within 1 percent (fig. 13). The intermediate shade data set has the lowest R^2, 2 percent, and a P_f value of 0.46, whereas the other two sets had P_f of 0.01 and 0.00. Thus, while there is strong repeatability of observed mean-differences at low and high shade, there is not for intermediate shade.

Some of the uncertainty may be due to the source of the mid-shade-level data. Much of it comes from Alaska where the low sun angles often cause less heating and drying. Sorting by shade may not be the best choice for illustrating model capability.

Furthermore, amount of shade caused by canopies is not an independent variable collected on-site; it is calculated by the BEHAVE model and combined with cloud shade to give percentage shade. Thus, partial results from one model are used in the analysis by shade level for testing all three models.

Model comparisons by fuel type are shown in table 2. (Note that the table is not meant to reflect a separate fuel type effect.) Data from the Alaska hardwood sticks and leaf litter, as well as the conifer sticks from both Alaska and Arizona, indicate that the BEHAVE and FFMC models are directly comparable and have small mean errors ranging from −1.45 to 0.577 percent, whereas the FBO model has large negative mean errors ranging from −3.55 to −6.53 percent. Grass data from Texas and pine needle data from Arizona reflect more favorably toward the BEHAVE and FBO models. This is probably attributable to the more open sites. Although the Idaho data consist of only six cases, the results typify the tendency of all three models to underpredict at the Idaho site. In all stratifications tried, the BEHAVE model performed best.

Table 2.—Comparison of the three moisture models, sorted by fuel types

Model	Mean error ($\bar{X}$)	Standard deviation (S)	Sample size (N)	Confidence			Contrasts P-level		
				P_1	P_3	I_{90}	1	2	3
				-- *Percent* --			--- *Percent* ---		
Conifer sticks (Alaska spruce, Arizona pine)									
FFMC	−0.80	5.61	30	27	49	±10.6	—	97	5
BEHAVE	−.84	5.72	30	27	49	±10.7	97	—	5
FBO	−3.55	4.82	30	29	54	±11.8	5	5	—
							P_F = 0.08, R^2 = 6%		
Hardwood sticks (Alaska)									
FFMC	−1.45	4.70	37	22	47	±9.3	—	100	0
BEHAVE	−1.45	4.70	37	22	47	±9.3	100	—	0
FBO	−5.65	6.01	37	14	37	±15.6	0	0	—
							P_F = 0.00, R^2 = 13%		
Leaf litter (Alaska)									
FFMC	0.57	7.32	47	9	49	±13.3	—	100	0
BEHAVE	.57	7.32	47	9	49	±13.3	100	—	0
FBO	−6.53	5.27	47	9	19	±15.2	0	0	—
							P_F = 0.00, R^2 = 20%		
Grass (Texas)									
FFMC	1.94	4.55	31	18	44	±7.0	—	5	1
BEHAVE	−.39	4.66	31	45	65	±7.7	5	—	57
FBO	−1.03	4.24	31	42	77	±7.0	1	57	—
							P_F = 0.03, R^2 = 8%		
Needles (Arizona pine)									
FFMC	1.63	2.73	71	29	78	±4.3	—	51	1
BEHAVE	1.33	2.72	71	37	80	±4.3	51	—	6
FBO	.47	2.79	71	29	77	±3.9	1	6	—
							P_F = 0.03, R^2 = 3%		
Litter (Idaho)									
FFMC	−4.68	2.92	6	0	27	±8.8	—	41	51
BEHAVE	−2.97	3.86	6	8	33	±8.4	41	—	21
FBO	−6.17	4.36	6	0	17	±14.3	51	21	—
							P_F = 0.36, R^2 = 13%		

The relative accuracy of the three models is illustrated by ranking them for mean error, P_1 level, and P_3 level in tables 3, 4, and 5, respectively. In table 3 (mean error) the BEHAVE model ranked first or tied for first in four of six fuel types; BEHAVE was second twice and never last. The ties can be attributed to shading and less heating in Alaskan fuels where BEHAVE reverts to the FFMC. For both confidence level P_1 and P_3 (tables 4 and 5), BEHAVE is first or tied for first in five of six fuel types, is tied for second once, and is never last. Whether the changes to the FFMC which resulted in the BEHAVE model really produced an equal or better model can be strongly inferred from the results of these three tables wherein the FFMC only ranked better than BEHAVE in one example, the mean error in conifer sticks, and in that case the difference is insignificant: −0.80 compared to −0.84.

Table 3.—Ranking the three moisture models by daily mean error X, percent

Fuel	First		Second		Third	
Grass (Texas)	BEHAVE	−0.39	FBO	−1.03	FFMC	1.94
Needles (Arizona)	FBO	0.47	BEHAVE	1.33	FFMC	1.63
Leaf litter (Alaska)	BEHAVE FFMC	0.57			FBO	−6.53
Conifer sticks (Alaska and Arizona)	FFMC	−0.80	BEHAVE	−0.84	FBO	−3.55
Hardwood sticks (Alaska)	BEHAVE FFMC	−1.45			FBO	−5.65
Conifer litter (Idaho)	BEHAVE	−2.97	FFMC	−4.68	FBO	−6.17

Table 4.—Ranking the three moisture models by confidence level P_1

Fuel	First		Second		Third	
Grass (Texas)	BEHAVE	45	FBO	42	FFMC	18
Needles (Arizona)	BEHAVE	37	FFMC FBO	29		
Conifer sticks (Alaska and Arizona)	FBO	29	BEHAVE FFMC	27		
Hardwood sticks (Alaska)	BEHAVE FFMC	22			FBO	14
Leaf litter (Alaska)	all tie	9				
Conifer litter	BEHAVE	8	FFMC FBO	0		

Table 5.—Ranking the three moisture models by confidence level P_3

Fuel	First		Second		Third	
Needles (Arizona)	BEHAVE	80	FFMC	78	FBO	77
Grass (Texas)	BEHAVE	65	FBO	77	FFMC	44
Conifer sticks (Alaska and Arizona)	FBO	54	BEHAVE FFMC	49		
Leaf litter (Alaska)	BEHAVE FFMC	49			FBO	19
Hardwood sticks (Alaska)	BEHAVE FFMC	47			FBO	37
Conifer litter (Idaho)	BEHAVE	33	FFMC	27	FBO	17

The variances, S^2, and confidence interval results, P_1, P_2, and I_{90}, are important operationally. As indicated by the low R^2 values (table 6), there is a lot of noise unrelated to model choice. Two results that stand out are the large error dispersions for the FBO model in Alaska hardwood sticks and leaf litter and Idaho conifer litter.

Table 6.—Summary of initialization verification for options 2, 3, and 5 of the BEHAVE moisture model

Option	Mean error ($\bar{X}$)	Variance (S)	Sample size (N)	Confidence			Contrasts P-level		
				P_1	P_3	I_{90}	2	3	5
Percent				-- *Percent* --					
2	−1.78	13.5	29	28	53	±6.4	—	22	—
3	−1.01	15.4	29	30	56	±5.9	22	—	—
5	+1.16	57.5	29	32	53	±14.4	—	—	—

Initialization Validation (Objective No. 2)

Initialization estimates the previous day's 1400-hour fine fuel moisture, referred to as m_o. It is a reference value and is not displayed to the user. Because fine fuels respond relatively fast, this value need not be highly accurate, but it does have a large range, from 2 percent to over 100 percent, which requires a good estimate. The test of the initialization process should confirm a reasonable estimate of m_o.

There are five options for initiating the BEHAVE model in midseason. Validation requirements differ by option.

Option 1 accepts a known fine fuel moisture; hence no validation is necessary.

Option 2 uses the full set of weather inputs just as the FFMC was designed to be operated and so becomes a standard for comparison.

Option 3 presumes it has rained within the past week and makes several assumptions about weather conditions within the intervening time period. It should be compared with option 2.

Option 4 uses persistence forecasting. It presumes that the weather has been stable for several days, so that fine fuels will approach a similar early afternoon moisture each day. Today's early afternoon weather fine-tunes it to today's conditions. No validation is presumed to be necessary.

Option 5 is a last resort if none of the first four options are applicable. It is an approximation that needs validation.

Option 3 is tested by comparing it with option 2. Early afternoon moisture data that included precipitation within the preceding 2 to 7 days were selected. This provided 29 cases for which both options can be exercised.

Exercising option 2 (table 6) on these cases, the values of the mean error (X_2), variance (S_2^2), and the relative frequencies P_1 and P_3 are:

$$\bar{X}_2 = -1.78,\ S_2^2 = 13.5,$$
$$P_1 = 0.28,\ P_3 = 0.53.$$

Exercising option 3, we obtain

$$\bar{X}_3 = -1.01,\ S_2^2 = 15.4,$$
$$P_1 = 0.30,\ P_3 = 0.56.$$

Using the F-test, it can be shown that an assumption of equal variances is reasonable for the two error distributions.

The differences between the P_1-values and between the P_3-values had P values of 0.59 and 0.48, respectively. This test is based on the binomial process with 29 trials. A Student-t statistic computed from $X_3 - X_2$ had a P value of 0.22.

In conclusion, option 3 is about as accurate (perhaps slightly better) on three of the four tests, having (perhaps) a slightly higher variance than option 2.

Initialization by use of option 5 was simulated by using the same 29 cases, but with the period length reduced to 1 day of propagation and the first fuel moisture set to 6, 16, or 76 percent. The three fuel moisture levels represent the three possible qualitative descriptions of the preceding week's weather. To simulate this, the equilibrium fuel moisture was computed for each day and averaged. The closest of the three moisture levels (6, 16, or 76) to this average was chosen as the initial value to use.

Exercising this simulated option 5:

$$\overline{X}_5 = 1.16,\ S^2 = 57.5,\ P_1 = 0.32,\ P_3 = 0.53$$

The F-ratio S_5^2/S_2^2 is significant at <0.005; consequently, a meaningful comparison of the mean errors of options 2 and 5 requires a different method. Assuming normally distributed mean errors and that the actual error variances are 13.4 and 57.5, respectively, then

$$(\overline{X}_2 - u)/(13.4/29)^{1/2} \text{ and } (\overline{X}_5 - u)/(57.5/29)^{1/2}$$

are normal random variables with a mean of zero and variance of 1. The hypothesis that X_2 and X_5 have the same mean (μ) can be tested. The sample values of these two standardized random variables are -0.48 and $+0.48$, respectively. The probability of that is $(0.32)^2$ or 0.10; the means are different at a significance level of 10 percent. Differences between the P_1- and P_3-values are significant at 0.43 and 0.63, respectively, for the 29-trial binomial tests.

Option 5 generates errors having a mean which is quite different from that of option 2 and much greater variance. The scores P_1 and P_3 are not significantly different, however.

Based on rather noisy data, it is apparent that option 3 is as good as option 2, while only the large errors are worsened by the use of option 5 in place of option 2. Evidently, any difference between the true values of P_1 and P_3 is sometimes masked by data noise if we assume that extra input information cannot harm model performance.

Validation of Diurnal Capability (Objective No. 3)

Validation of diurnal capability is concentrated on the BEHAVE model using the Canadian code with hourly prediction capability. This is because neither the FBO model nor the tables developed by the Canadian Forestry Service (Van Wagner 1972; Alexander 1982) for the FFMC have the forecasting capabilities needed for the BEHAVE system.

Sackett (1983, 1984) collected fine fuel moisture data over 24-hour periods during June and October 1983 in northern Arizona. This provided a chance to test the model with high and low sun angles. He also collected data beneath three densities of crown canopy. These data are summarized in table 7. Prediction from the BEHAVE diurnal model using these data are shown in table 8.

Table 7.—Summary of diurnal data taken in northern Arizona by Steve Sackett in 1983

Time	Observed weather T_a	H_a	U_{10}	S_c	Measured fuel moisture C = 4.4	C = 74	C = 94
	°F	Pct	Mi/h		Percent		
Date - 6/28/83, Elevation - 7,440 ft, Aspect - 225°, Slope ≅ 4%, T_{SR} - 4.8, T_{SS} - 19.2							
1516	76	11	5-12	10	3.3	3.4	4.2
1614	75	15	8-13	10	2.8	3.4	4.0
1725	75	17	9-13	10	3.2	3.5	4.0
1810	71	18	8-12	0	4.0	3.8	4.4
1908	67	23	0- 5	0	3.75	4.1	5.8
2117	52	37	0- 4	0	4.3	4.8	5.7
2218	50	37	0- 3	0	7.3	5.1	5.4
2357	50	37	0- 2	0	4.9	5.8	6.0
0157	47	42	0- 4	0	5.0	6.1	5.7
0403	46	41	0- 3	0	6.2	5.9	7.0
0550	41	53	0	0	6.2	6.2	7.4
0700	53	48	0	0	6.0	7.05	7.7
0815	64	20	0-10	0	4.3	6.6	7.0
0940	70	20	8-12	0	4.1	5.3	6.1
1040	75	15	8-12	0	3.3	4.4	5.4
1140	76	11	8-12	0	3.4	4.2	3.9
Date - 10/20/83, Elevation - 7,440 ft, Aspect - 225°, Slope ≅ 4%, T_{SR} - 6.5, T_{SS} - 17.5							
1310	61	23	0- 5	0	9.0	8.0	13.1
1510	63	15	5-10	0	5.0	9.0	10.7
1710	57	22	3- 6	10	6.6	8.9	11.8
1910	40	58	0	0	12.25	10.7	13.6
2030	37	63	0- 2	0	15.1	10.3	14.0
2230	31	72	0	0	11.3	13.7	14.6
0130	27	77	0- 2	0	11.6	13.0	15.0
0330	27	77	0- 1	0	11.4	12.8	14.3
0945	57	30	2- 5	0	8.9	11.4	15.2
1210	63	25	5- 8	0	8.3	13.95	11.9

Table 8.—Calculations from the BEHAVE diurnal model with data from northern Arizona

Time	T_a	H_a	U_{10}	Crown closure = 4.4% S_h	m	Crown closure = 74% S_h	m	Crown closure = 94% S_h	m
				June 28, 1983		≅			
1400	77	8	8	15	3.4	82	3.4	91	4.3
1516	76	9	7	15	2.6	90	3.4	95	4.1
1614	75	11	6	16	2.3	96	3.4	98	4.1
1725	72	17	5	16	2.4	100	3.4	100	4.1
1810	70	18	4	20	2.7	100	3.5	100	4.2
1908	67	23	3	36	2.8	100	3.8	100	4.4
2117	58	31	3	100	3.7	100	4.5	100	4.7
2218	55	34	3	100	4.1	100	4.9	100	5.0
2357	50	38	2	100	4.9	100	5.7	100	6.1
0157	45	43	2	100	5.7	100	6.5	100	6.9
0403	43	45	2	100	6.7	100	7.4	100	7.7
0550	44	44	3	100	7.2	100	8.0	100	8.4
0700	46.5	41.0	4.2	32	7.4	100	8.4	100	8.7
0815	52	34	6	10	7.2	95	8.7	98	8.9
0940	62	26	8	7	6.0	85	8.7	88	8.9
1040	69	18	9	5	5.0	76	8.4	82	8.5
1140	76	11	10	5	4.5	69	7.8	75	8.0
				October 20, 1983		≅			
1400	61	20	5	14	6.7	97	8.4	98	12.1
1510	60	21	5	15	6.4	98	8.3	99	11.6
1710	57	32	4	36	6.7	100	8.4	100	11.2
1910	47	44	4	100	7.4	100	8.9	100	11.3
2030	43	50	3	100	8.0	100	9.3	100	11.5
2230	37	58	3	100	9.0	100	10.2	100	12.1
0130	31	69	2	100	10.8	100	11.7	100	13.2
0330	28	74	2	100	11.9	100	12.6	100	14.0
0945	40	55	.5	16	13.5	99	14.9	99	15.9
1200	63	25	6.5	10	10.4	93	13.9	96	15.6

Predictions by the BEHAVE model of temperature, humidity, and moisture from 1400 one day to 1200 (noon) the next are shown in figures 14 to 18. For these predictions the model was given initial weather and moisture at 1400. In place of forecasts at sunset and sunrise, it was given measured weather and the final value. Hourly predictions of T, H, and m are plotted as lines for comparison with the measured data points.

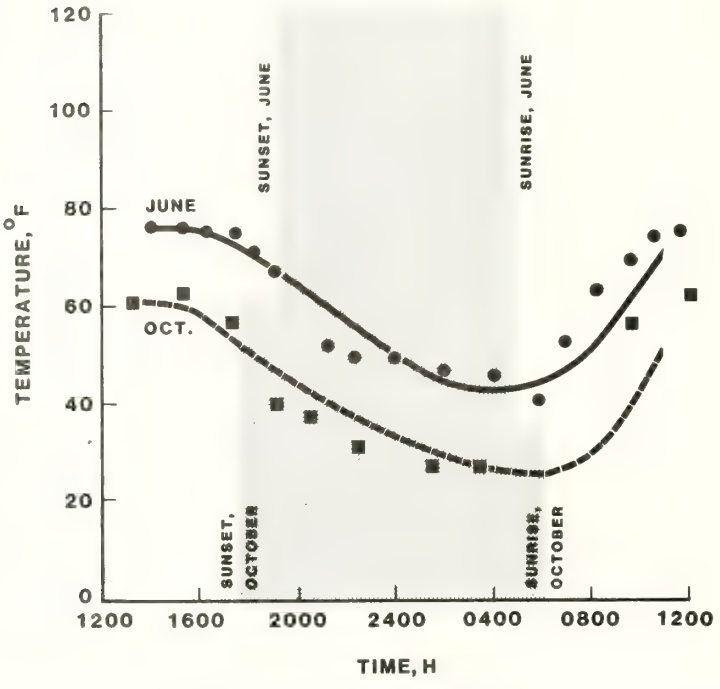


Figure 14.—Diurnal temperature measurements (dots and squares) and model predictions (lines) for June and October in Arizona.

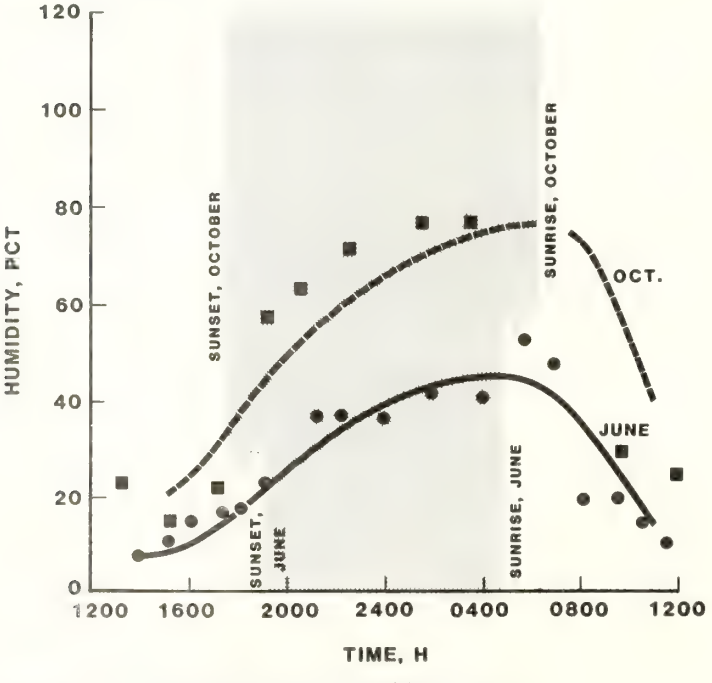


Figure 15.—Diurnal relative humidity measurements (dots and squares) and model predictions (lines) for June and October in Arizona.

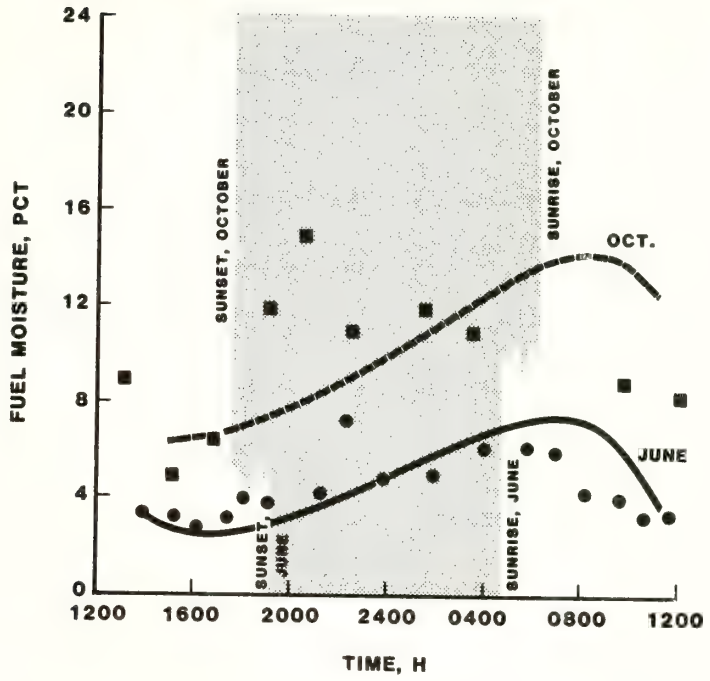


Figure 16.—Diurnal fuel moisture measurements (dots and squares) and model predictions (lines) for June and October in Arizona beneath a 4.4 percent crown closure ponderosa pine stand.

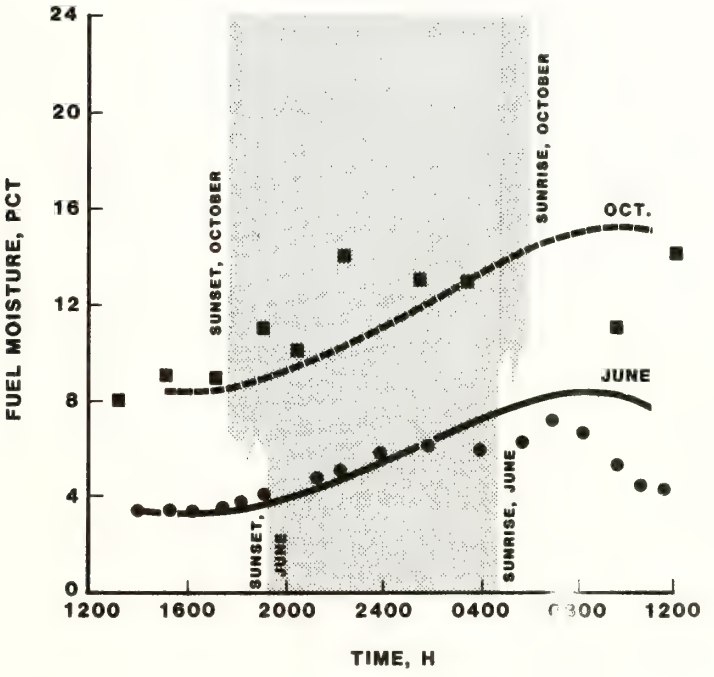


Figure 17.—Diurnal fuel moisture measurements (dots and squares) and model predictions (lines) for June and October in Arizona beneath a 74 percent crown closure ponderosa pine stand.

CLEMSON UNIVERSITY LIBRARY
PUBLIC DOCUMENTS DEPT.

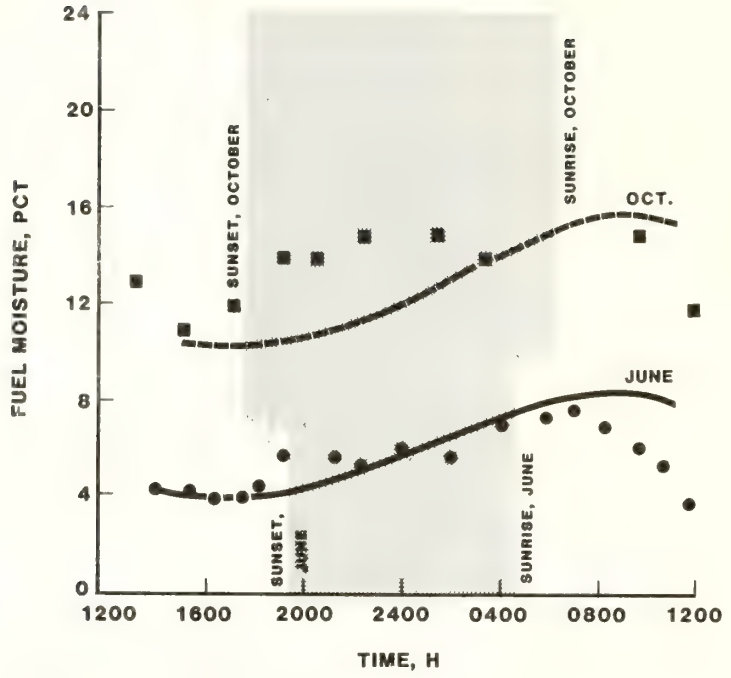


Figure 18.—Diurnal fuel moisture measurements (dots and squares) and model predictions (lines) for June and October in Arizona beneath a 94 percent crown closure ponderosa pine stand.

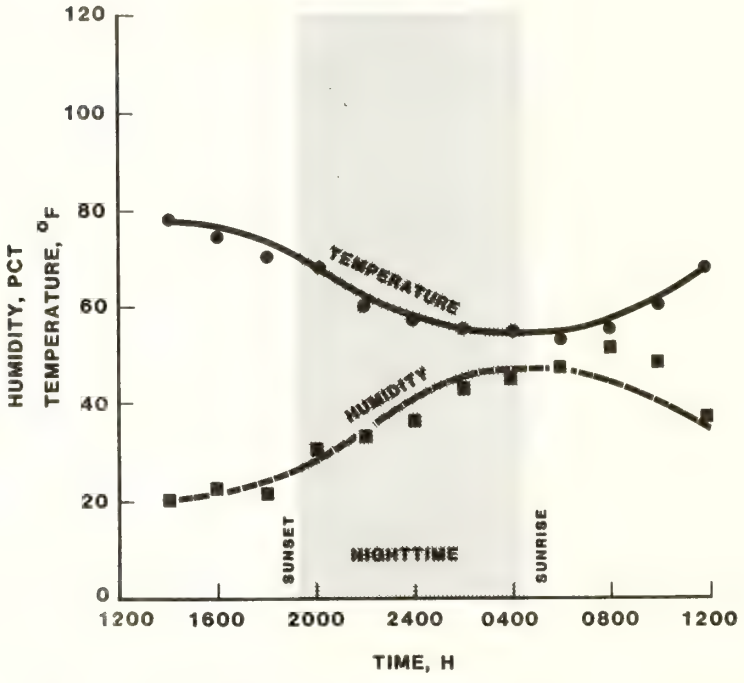


Figure 19.—Diurnal temperature and humidity measurements (dots and squares) and model predictions (lines) in Idaho in August beneath mixed conifer stand.

We also have diurnal temperature and humidity data collected by Frandsen and Bradshaw at four sites in Idaho. Their moisture data were collected only in the morning, the most difficult period for prediction. Data from their site 3 in August and September illustrate the model's ability to predict temperature and humidity under a mixed conifer stand in a mountain location (figs. 19 and 20).

Summaries of the performance of the BEHAVE and FBO models for afternoon, night, and morning hours are shown in table 9. Two sets of morning data are presented—one for Sackett's open stand and one for the Idaho data. The BEHAVE model performed very well, capturing 77 percent of the afternoon data within 1 percent of measured and 100 percent within 2 percent. During the night it captured 50 percent within 1 percent and 67 percent within 2 percent. In the morning it captured 29 percent within 1 percent and 86 percent within 2 percent. In Idaho, these latter figures fell off to 14 percent and 46 percent. The FBO performance was considerably less in all cases.

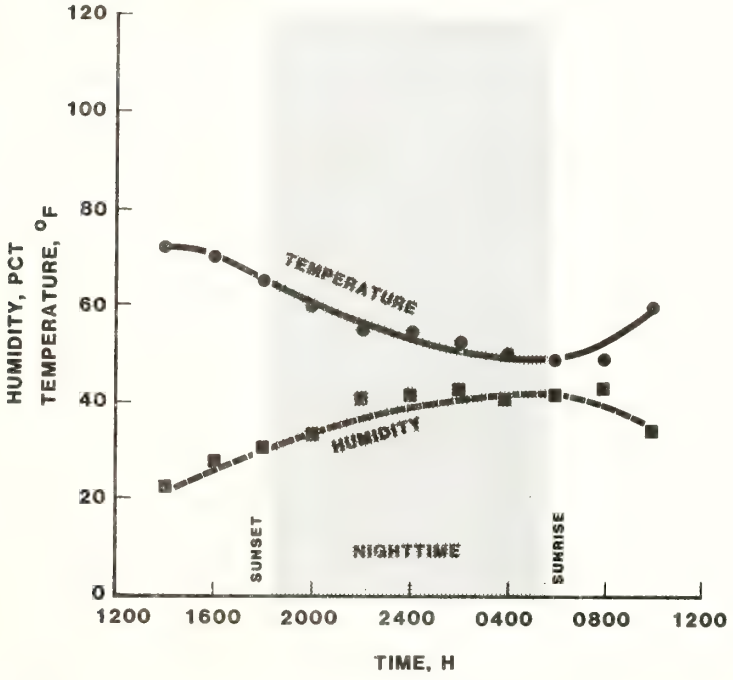


Figure 20.—Diurnal temperature and humidity measurements (dots and squares) and model predictions (lines) in Idaho in September beneath mixed conifer stand.

Table 9.—Summary of fine fuel moisture litter data from Arizona and Idaho by period of the day ($\bar{X}$ = mean error, S^2 = error variance)

Place	Time of day	Model	$\bar{X}$	S^2	P_1	P_2	I_{90}	n	Shade
									Percent
Arizona	Afternoon (after 1400)	BEHAVE	−0.25	0.39	77	100	1.2	13	9-100
	Afternoon (after 1400)	FBO	1.6	5.5	23	38	4.2	13	9-100
	Night	BEHAVE	−1.7	5.8	50	67	5	12	100
	Night	FBO	3.4	9.5	0	17	6.1	12	100
	Morning (before 1200)	BEHAVE	1.5	.51	29	86	2.5	7	4-40
	Morning (before 1200)	FBO	2.7	4.1	29	29	4.5	7	4-40
Idaho	Morning (before 1200)	BEHAVE	−3.4	11.4	14	46	8.2	35	26-95
	Morning (before 1200)	FBO	−6.4	12.8	0	9	12.1	35	26-95

The statistical summary indicates that the BEHAVE diurnal model performs very well. Figures 14 through 20 reveal more about its capabilities. Predictions of temperature and humidity through the late afternoon and night are surprisingly accurate, in both Arizona and Idaho. An exception may be in the predictions of temperature and humidity in October in Arizona. The trend of the actual data is followed, but through the night actual temperatures are about 5° cooler than predicted and humidities about 10 percent higher. As shown in the October fuel moisture predictions (figs. 16, 17, and 18), moisture is underpredicted during the night.

In the morning the model responds fastest for conditions in the open stand (fig. 16) because the solar heating functions bring the predicted fuel moisture down faster than in the shaded sites (figs. 17 and 18). More diurnal data are needed to determine if these effects are persistent enough to warrant changes to the model.

REFERENCES

Albini, Frank A.; Baughman, Robert G. Estimating windspeeds for predicting wildland fire behavior. Research Paper INT-221. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979. 12 p.

Albini, F. A. Computer-based models of wildland fire behavior: a users' manual. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1976. 68 p.

Alexander, M. E. Diurnal adjustment table for the Fine Fuel Moisture Code. Forest Management Note No. 17. Edmonton, AB: Environment Canada, Canadian Forestry Service, Northern Forest Research Centre; 1982. 3 p.

Alexander, M. E.; Lee, B. S.; Lee, C. Y. Hourly calculation of the Fine Fuel Moisture Code, Initial Spread Index, and Fire Weather Index with the Texas Instruments model 59 hand-held calculator. Study NOR-5-191 File Report No. 7. Edmonton, AB: Agriculture Canada, Canadian Forestry Service, Northern Forest Research Centre; 1984. 17 p.

Anderson, H. E. Moisture and fine forest fuel response. In: Proceedings, eighth national conference on fire and forest meteorology; 1985 April 29-May 30; Detroit, MI. [In press].

Andrews, P. L. BEHAVE: fire behavior prediction and fuel modeling system—BURN subsystem. General Technical Report INT-194. Ogden, UT: Department of Agriculture, Forest Service, Intermountain Research Station; 1986.

Barbour, M. G.; Burk, J. H.; Pitts, W. D. Terrestrial plant ecology. Menlo Park, CA: Ben Cummings Publishing Company; 1980. 604 p.

Barrows, Jack S. Forest fires in the Northern Rocky Mountains. Station Paper No. 28. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Rocky Mountain Forest and Range Experiment Station; 1951. 251 p.

Bates, C. G.; Henry, A. J. Forest and stream flow experiment at Wagon Wheel Gap, Colorado. Monthly Weather Review. 56(3): 79-85; 1928.

Buck, Arden L. New equations for computing vapor pressure and enhancement factor. Journal of Applied Meteorology. 20: 1527-1532; 1981.

Burgan, R. E.; Rothermel, R. C. BEHAVE: fire behavior prediction and fuel modeling system—FUEL subsystem. General Technical Report INT-167.

Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 126 p.

Byram, G. M. Sun and wind and fuel moisture. Journal of Forestry. 38: 639-640; 1940.

Byram, G. M.; Jemison, G. M. Solar radiation and forest fuel moisture. Journal of Agricultural Research. 67(4): 149-176; 1943.

Canadian Forestry Service. Tables for the Canadian Forest Fire Weather Index System. Forestry Technical Report 25. Ottawa, ON: Environment Canada, Canadian Forestry Service; 1984. 48 p.

Catchpole, E. A.; Catchpole, W. R. Analysis of the 1972 Darwin grass fires. Report No. 3. Duntroon, A.C.T., Australia: The University of New South Wales, Faculty of Military Studies, Department of Mathematics; 1983. 67 p.

Clark, Robert G. [Letters to Richard C. Rothermel]. 1981 September 2 and September 16. 9 leaves and 15 leaves. Located at: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Intermountain Fire Sciences Laboratory, Missoula, MT; RWU 2103 files.

Countryman, Clive M. Radiation effects on moisture in ponderosa pine litter. Research Paper PSW-126. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1977. 23 p.

Deeming, John E.; Lancaster, James W.; Fosberg, Michael A.; Furman, R. William; Schroeder, Mark J. National Fire-Danger Rating System. Research Paper RM-84. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1972. 165 p.

Fischer, William C.; Hardy, Charles E. Fire-weather observers' handbook. Agriculture Handbook 494. Washington, DC: U.S. Department of Agriculture, Forest Service; 1976. 152 p.

Fosberg, Michael A.; Deeming, John E. Derivation of the 1- and 10-hour time-lag fuel moisture calculations for fire-danger rating. Research Note RM-207. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1971. 8 p.

Frandsen, W. H.; Bradshaw, L. Estimating duff moisture from meteorological measurements. In: Proceedings, sixth conference on fire and forest meteorology; 1980 April 22-24; Seattle, WA. Washington, DC: Society of American Foresters; 1980: 96-101.

Frank, E. C.; Lee, R. Potential solar beam irradiation on slopes: tables for 30° to 50° latitude. Research Paper RM-18. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1966. 116 p.

Gast, P. R.; Stickel, P. W. Solar radiation and relative humidity in relation to duff moisture and forest fire hazard. Monthly Weather Review. 1929 November 7: 466-468.

Gisborne, H. T. Measuring forest fire danger in northern Idaho. Miscellaneous Publication No. 29. Washington, DC: U.S. Department of Agriculture; 1928. 63 p.

Gisborne, H. T. Deadwood lying on duff drier than in air. Journal of Forestry. 31(8): 979-980; 1933.

Gisborne, H. T. The principles of measuring forest fire danger. Journal of Forestry. 34: 786-793; 1936.

Harrington, M. G. [Letter to Richard C. Rothermel]. 1983 July 6. 6 leaves. Located at: U.S. Department of Agriculture, Forest Service, Intermountain

Forest and Range Experiment Station, Intermountain Fire Sciences Laboratory, Missoula, MT; RWU 2103 files.

Hornby, L. G. Fuel type mapping in Region One. Journal of Forestry. 33: 67-72; 1935.

Johnson, J. C. Physical meteorology. 2d ed. New York: J. Wiley & Sons; 1960. 393 p.

Jordan, C. F. Derivation of leaf-area index from quality of light on the forest floor. Ecology. 50: 663-666; 1969.

Kaufmann, M. R.; Weatherred, J. D. Determination of potential direct beam solar irradiance. Research Paper RM-242. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1982. 23 p.

Kimball, H. H. Variations in the total and luminous solar radiation with geographical position in the United States. Monthly Weather Review. 47(11): 769-793; 1919.

Kondratyev, K. Ya. Radiation in the atmosphere. New York: Academic Press; 1969. 912 p.

Lee, R. Theory of the "Equivalent Slope." Monthly Weather Review. 90: 165-166; 1962.

List, R. J. Smithsonian meteorological tables. 6th ed. Washington, DC: Smithsonian Institute Publishing Company; 1958. 527 p.

Loewe, F. The intake of solar radiation by slopes with cloudless sky. Bulletin No. 45. Melbourne: Commonwealth of Australia, Bureau of Meteorology; 1962. 57 p.

Luke, R. H.; McArthur, A. G. Bushfires in Australia. Canberra, Australia: Australian Government Publishing Service; 1978. 359 p.

Milankovetch, M. Mathematische Klimalehre. Handbuch der Klimatologische, Bank I, Teil A: 1-176; 1930.

Monsi, M.; Saeki, T. Uber den Lichtfaktor in den Pflanzengesellschaften und seine Bedeutung fur die Stoffproduktion. Japanese Journal of Botany. 14: 22-52; 1953.

Muraro, S. J.; Russel, R. N.; Lawson, B. D. Development of diurnal adjustments table for the Fine Fuel Moisture Code. Information Report BC-X-35. Victoria, BC: Department of Fisheries and Forestry, Forest Research Laboratory; 1969. 24 p.

Norum, Rodney A. [Letter to Richard C. Rothermel]. 1983 February 22. 29 leaves. Located at: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Intermountain Fire Sciences Laboratory, Missoula, MT.

Okanoue, Masco. On the intensity of solar radiation on any slope. Japanese Forestry Society Journal. 39(11): 435-437; 1957.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 174 p.

Plummer, F. G. Forest fires: their causes, extent, and effects, with a summary of recorded destruction and loss. Forest Service Bulletin 117. Washington, DC: U.S. Department of Agriculture; 1912. 39 p.

Rothermel, Richard C. A mathematical model for predicting fire spread in wildland fuels. Research Paper INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1972. 40 p.

Rothermel, Richard C. How to predict the spread and intensity of forest and range fires. General Technical Report INT-143. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 161 p.

Running, Steven W.; Hungerford, Roger D. Spatial extrapolation of meteorological data for ecosystem modeling applications. In: Proceedings, 16th conference on agriculture and forest meteorology; 1983 April 25-29; Fort Collins, CO. Boston, MA: American Meteorological Society; 1983: 4 p., unnumbered proceedings.

Sackett, Stephen S. [Letters to Richard C. Rothermel]. 1983 September 10, 4 leaves and 1984 January 10, 5 leaves. Located at: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Intermountain Fire Sciences Laboratory, Missoula, MT; RWU 2103 files.

Salomon, R. M.; Ffolliott, P. F.; Thompson, J. R. Correlation between transmissivity and basal area in Arizona ponderosa pine forests. Research Note RM-318. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1976. 2 p.

Satterlund, D. R. Forest shadows: how much shelter in a shelterwood? Forest Ecology and Management. 5: 27-37; 1983.

Schroeder, Mark J.; Buck, Charles C. Fire weather . . . a guide for application of meteorological information to forest fire control operations. Agriculture Handbook 360. Washington, DC: U.S. Department of Agriculture; 1970. 229 p.

Simard, A. J. [Letter to Richard C. Rothermel]. 1984 October 3. 2 leaves. Located at: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Intermountain Fire Sciences Laboratory, Missoula, MT; RWU 2103 files.

Simard, A. J.; Main, W. A. Comparing methods of predicting jack pine slash moisture. Canadian Journal of Forest Research. 12(4): 793-802; 1982.

Stage, A. R. An expression for the effect of aspect, slope, and habitat type on tree growth. Forest Science. 22(4): 457-460; 1976.

Turner, J. A.; Lawson, B. D. Weather in the Canadian Forest Fire Danger Rating System. Information Report BC-X-177. Victoria, BC: Pacific Forest Research Centre; 1978. 40 p.

Van Wagner, C. E. Combined effect of sun and wind on surface temperature of litter. Information Report PS-X-10. Chalk River, ON: Forestry Branch, Department of Fisheries and Forestry, Petawawa Forest Experiment Station; 1969. 7 p.

Van Wagner, C. E. A table of diurnal variation in the Fine Fuel Moisture Code. Information Report PS-X-38. Chalk River, ON: Environment Canada, Canadian Forestry Service, Petawawa Forest Experiment Station; 1972. 8 p.

Van Wagner, C. E. Structure of the Canadian Forest Fire Weather Index. Publication No. 1333. Ottawa, ON: Environment Canada, Canadian Forestry Service; 1974. 44 p.

Van Wagner, C. E. A method of computing fine fuel moisture content throughout the diurnal cycle. Information Report PS-X-69. Chalk River, ON: Fisheries and Environment Canada, Canadian Forestry Service, Petawawa Forest Experiment Station; 1977. 15 p.

Zavitkovski, J. Biomass studies in intensively managed forest stands. General Technical Report NC-21. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1976. 117 p.

NOMENCLATURE

Symbol	Definition	Units
A	elevation angle to the sun ($-90° \leq A \leq 90°$)	degrees
A_b	bole shadow area	square feet
A_h	shadow area projected on a horizontal reference plane by the sun at solar altitude A	square feet
A_h'	net "effective" tree shadow	square feet
A_s	vertical projection of S onto the horizontal	square feet
A_s'	vertically projected crown area of one tree	square feet
A_u	horizontal unit surface area	acres
C	crown closure	percent
d	tree bole diameter	feet
D	crown diameter	feet
D_y	day of month	days
E	elevation above sea level	feet
G	horizontal angular coordinate of tangential solar ray in conifer crown	
G′	vertical angular coordinate of tangential solar ray in deciduous crown	
h	tree bole height	feet
h*	hour angle from the local 6 a.m.	degrees
h′	vegetation height	feet
H	relative humidity at time t	percent
H_a	relative humidity of air	percent
H_f	relative humidity adjacent to fuel	percent
H_r	relative humidity at sunrise	percent
H_s	relative humidity at sunset	percent
H_{14}	relative humidity at 1400	percent
I	incident radiation intensity on the forest floor	cal/cm^2•min
I_a	irradiance at the forest floor perpendicular to the solar ray	cal/cm^2•min
I_M	incident radiation attenuated by the atmosphere	cal/cm^2•min
I_o	solar constant (= 1.98 cal/cm^2•min); incident solar radiation on the upper atmosphere	cal/cm^2•min
J	extinction coefficients for attenuation function	ft^{-1}
k	log drying rate	
l	projection of radial coordinate, r′, perpendicular to solar ray	feet
l_M	optical path length of direct solar radiation through the atmosphere	feet
l_z	optical path length at the zenith at elevation E	feet
l_{zo}	optical path length at sea level zenith	feet
L	crown height	feet
m_o	initial fuel moisture	percent
M	optical air mass	
M_o	month	

NOMENCLATURE (Con.)

Symbol	Definition	Units
n	number of trees on unit area	
N_n	fractional area shaded by n average trees per unit of horizontal surface area	
N_J	Julian date	days
p	transparency coefficient (= 0.745)	
r	earth-sun (center of mass) distance multiples of mean value	
r′	radial coordinate of tangential solar ray on deciduous crowns	feet
S_c	cloud cover	percent
t	reference time (local standard)	hours since midnight
t_p	projection time	hours since midnight
t_r	time of sunrise	hours since midnight
t_s	time of sunset	hours since midnight
T	temperature at time t	°F
T_a	air temperature	°F
T_f	fuel temperature	°F
T_p	temperature at projection time	°F
T_r	temperature at sunrise	°F
T_s	temperature at sunset	°F
T_{14}	temperature at 1400	°F
U	wind velocity	mi/h
$U_{h'}$	windspeed at vegetation height	mi/h
$U_{20+h'}$	windspeed at 20 feet above vegetation	mi/h
V	crown volume	cubic feet
X	intracrown path length	feet
z	solar azimuth	degrees
α	slope angle from horizontal at slope azimuth	degrees
β	aspect of slope (the azimuth)	degrees
δ	solar declination	degrees
ϵ	Julian date correction for February and leap years	
ζ	solar angle to the slope in the plane normal to the slope	degrees
ϱ	absolute atmospheric pressure at the site	mb
ϱ_o	sea level pressure (= 1,000 mb)	mb
τ_n	net transmittance	-
τ_c	cloud transmittance	-
τ_t	tree transmittance	-
ψ	slope angle at solar azimuth z	degrees
ϕ	latitude	degrees

LIST OF EQUATIONS

$$T_f - T_a = I/(0.015U_{h'} + 0.026) \quad (1)$$

$$H_f = H_a \exp(-0.033(T_f - T_a)) \quad (2)$$

$$I = (I_a / r^2) \sin A \quad (3)$$

$$\sin A = \sin h^* \cos \delta \cos \phi + \sin \delta \sin \phi \quad (4)$$

$$\tan z = \frac{\sin h^* \cos \delta \sin \phi - \sin \delta \cos \phi}{\cos h^* \cos \delta} \quad (5)$$

$$\cos z = \cos h^* \cos \delta / \cos A \quad (6)$$

$$r^2 = 0.999847 + 0.001406(\delta)$$

$$\delta = 23.5 \sin(0.9863(284 + N_J)) \quad (7)$$

$$N_J = \text{Julian date}$$
$$= \text{Integer Value } (31(M_o - 1) + D_y - 0.4M_o - 1.3 + \epsilon) \quad (8)$$

$$I = I_a \sin \zeta \quad (9)$$

$$\sin \zeta = \sin(A - \psi)(\cos \alpha)/\cos \psi \quad (10)$$

$$\tan \psi = \tan \alpha \sin(z - \beta) \quad (11)$$

$$I_a = I_M \tau_n \quad (12)$$

$$I_M = I_o p^M \quad (13)$$

$$M = l_M/l_{zo} = l_z (\csc A)/l_{zo} \quad (14)$$

$$l_z = l_{zo} \varrho/\varrho_o \quad (15)$$

$$\varrho = \varrho_o \exp(-0.0000448E) \quad --$$

$$M = (\varrho/\varrho_o) \csc A = \exp(0.0000448E) \csc A \quad (16)$$

$$I_a = I_o \tau_n p^M \quad (17)$$

$$\tau_n = \tau_c \cdot \tau_t \quad (18)$$

$$\tau_c = (1 - S_c/100) \quad --$$

$$A_h = \pi D^2/4, \text{ for conifers, if } \tan A \geq 2L/D, \text{ or} \quad (19)$$
$$= (\pi - G)D^2/4 + DL \cot A \sin G, \text{ if } \tan A < 2L/D \quad (20)$$

$$\cos G = (2(L/D) \cot A)^{-1} \quad (21)$$

$$A_h = \pi D l/(2 \sin A) \text{ for deciduous} \quad (22)$$

$$l = r' \sin(G' - A) \quad (23)$$

$$\tan G' = -(L/D) \cot A \quad (24)$$

$$r' = (L/2)(\sin^2 G' + (L/D)^2 \cos^2 G')^{-1/2} \quad (25)$$

$$X = V/(A_h \sin A) \quad --$$
$$= \pi D^2 L/(12 A_h \sin A) \text{ for conifers} \quad (26)$$
$$= \pi D^2/(6 A_h \sin A) \text{ for deciduous} \quad (27)$$

$$A_b = (2/3) dh \cot A \quad (28)$$

$$A_h' = A_b + A_h (1 - \exp(-JX)) \quad (29)$$

$$A_s = A_h' (\cos \psi \sin A)/\sin(A + \psi) \quad (30)$$

$$N_1 = A_s / A_u \quad (31)$$

$$N_2 = N_1 (1 - N_1) + N_1 \quad --$$

$$N_3 = N_1 (1 - N_2) + N_2 \quad --$$

$$N_n = N_1 (1 - N_{n-1}) + N_{n-1} \quad --$$

$$N_n \cong 1 - \exp(-nN_1) \quad (32)$$

$$\tau_t = 1 - N_n = \exp(-nN_1) \quad (33)$$

$$A_s' = \pi D^2/4 \quad --$$

$$N_1' = A_s'/A_u \quad --$$

$$N_n' = C = 1 - \exp(-nN_1') \quad (34)$$

$$n = -ln(1 - C)/N_1'$$

LIST OF EQUATIONS (Con.)

$$n = -4A_n \, ln(1 - C)/\pi D^2 \quad (35)$$

$$U_{h'}/U_{20-h'} = 1/ln((20 + 0.36h')/0.13h') \quad (36)$$

$$k = a + b(U_{20})^{0.5} \quad (37)$$

$$T = T_{14} + (T_{14} - T_s)(\cos(90(t - 24)/(t_s - 14)) - 1) \quad (38)$$

$$H = H_{14} + (H_{14} - H_s)(\cos(90(t_s - 24)/(t - 14)) - 1) \quad (39)$$

$$T = T_s + (T_r - T_s) \sin(90(t - t_s)/(t_r - t_s)) \quad (40)$$

$$H = H_s + (H_r - H_s) \sin(90(t - t_s)/(t_r - t_s)) \quad (41)$$

$$T = T_{12} + (T_r - T_{12}) \cos(90(t - t_r)/(12 - t_r)) \quad (42)$$

$$H = H_r + (H_r - H_{12})(\cos(90(t - t_r)/(12 - t_r)) - 1) \quad (43)$$

APPENDIX A: CANADIAN STANDARD DAILY FINE FUEL MOISTURE CODE (FFMC)

(Adapted from Simard 1982.)

1. Adjust initial fuel moisture code (f_o) for rain (R) if R >0.02 inches.

$$R_A = \min(R,1.5)$$

$$F = \begin{cases} -56 - 55.6 \ln(R_A + 0.04) & \text{if } R_A \leq 0.055 \text{ inches} \\ -1 - 18.2 \ln(R_A - 0.04) & \text{if } 0.055 < R_A \leq 0.225 \text{ inches} \\ 14 - 8.25 \ln(R_A - 0.075) & \text{if } 0.225 < R_A \end{cases}$$

$$f_R = \max(0,(F \cdot f_o/100) + 1 - 8.73 \exp(-0.1117 f_o)$$

   if R ≤ 0.02 inches, $f_R = f_o$.

2. $m_R = 101 - f_R$
3. $E_D = (0.942H^{0.679}) + 11 \exp[(H/10) - 10]$
4. $E_W = (0.597H^{0.768}) + 14 \exp[(H/8) - 12.5]$
5. $m = E_W + (m_R - E_W)/1.9953$ if $m_R < E_D$
6. $X = 0.424(1 - (H/100)^{1.7}) + 0.088\, W^{0.5}(1 - (H/100)^8)$
7. $m = E_D + (m_R - E_D)/(10^x)$ if $m_R > E_D$
8. $m = m_R$ if $m_R = E_D$
9. $\triangle = \begin{cases} \max(-16.,(T - 70)(0.63 - 0.0065 f_R) & \text{if } f_o < 99\% \\ 0 & \text{if } f_o \geq 99\% \end{cases}$
10. $f = \max(0,\min(99,101-m+\triangle))$, fuel moisture $= 101 - f$.

Variable	Definition
f_o	initial fine fuel moisture code
T	temperature (°F)
H	relative humidity (%)
W	windspeed (between 1 and 14 mi/h at 20 feet or above)
R	rain (inches)
f_R	f_o modified for rain
E_D	equilibrium drying curve
E_W	equilibrium wetting curve
m_R	initial fuel moisture adjusted for rain (%)
m	fine fuel moisture adjusted for humidity and wind
$\triangle$	adjustment for temperature (%)
f	final FFMC

Explanation

Initial FFMC (f_o) is first adjusted to a value (f_R) based on the amount of rainfall (R) provided that R >0.02 inches. (Note: f_o is a code—when subtracted from 101, a fuel moisture percentage is obtained.)

If the adjusted initial fuel moisture (m_R) is above the drying curve (E_D), m is computed by equation 7. If m_R is below E_D, a wetting trend is in effect and m is computed from equation 5. If $m_R = E_D$, moisture is initially at or near equilibrium. m is set to the initial value m_R. Up to this point, temperature is ignored.

Finally, temperature is considered and the final FFMC (f) is computed from m by equations 9 and 10. f represents the new FFMC based on the initial value (f_o).

APPENDIX B: CANADIAN HOURLY FINE FUEL MOISTURE CODE

Listed below are the equations and basic instructions for the dry weather routine to be used in the hourly computation of the FFMC from Van Wagner (1977). Weather values are in SI units except wind which is in km/h.

(1) m_o = m calculated from Standard Daily FFMC

(2a) $E_d = 0.942H^{0.679} + 11\exp[(H - 100)/10] + 0.18(21.1 - T)(1 - \exp(-0.115H))$

(2b) $E_w = 0.618H^{0.753} + 10\exp[(H - 100)/10] + 0.18(21.1 - T)(1 - \exp(-0.115H))$

(3a) $k_a = 0.424\ [1-(H/100)^{1.7}] + 0.0694W^{0.5}\ [1 - (H/100)^8]$

(3b) $k_d = 0.0579\ k_a \exp(0.0365T)$

(4a) $k_b = 0.424\ [1-((100 - H)/100)^{1.7}] + 0.0694W^{0.5}\ [1-((100 - H)/100)^8]$

(4b) $k_w = 0.0579\ k_b \exp(0.0365T)$

(5a) $m = E_d + (m_o - E_d)\exp(-2.303\ k_d)$

(5b) $m = E_w - (E_w - m_o)\exp(-2.303\ k_w)$

where

m_o = initial fine fuel moisture (%)

m = final fuel moisture (%)

E_d = EMC for drying (%)

E_w = EMC for wetting (%)

k_a and k_b = intermediate steps to k_d and k_w

k_d = log drying rate for hourly computation, log to base 10

k_w = log wetting rate for hourly computation, log to base 10

H = relative humidity, %

W = wind, km/h ($\leq$ 22.5)

T = temperature, °C.

The Standard Daily FFMC provides the first m_o. Subsequently, the previous hour's m becomes m_o.

Compute E_d by (2a).

If $m_o > E_d$, compute k_d by (3a) and (3b).

Compute m by (5a).

If $m_o < E_d$, compute E_w by (2b).

If $m_o < E_w$, compute k_w by (4a) and (4b).

Compute m by (5b).

If $m_o = E_d$ or E_w, $m = m_o$.

If $E_d > m_o > E_w$, $m = m_o$.

Note that precipitation is not involved.

APPENDIX C: CORRECTION FOR INITIAL SHADE CONDITIONS IN FFMC

The correction for solar heating must consider the possibility of solar heating on the fuels that were used in the initial development of the Canadian Fine Fuel Moisture Code. It cannot be assumed that there was no solar heating even though the fuel moisture data were collected beneath a forest canopy and some of it possibly on cloudy days. In lieu of reconstruction of the initial conditions, that is, description of overstory and cloud conditions at the time of data collection, the concept of a threshold value was examined to see if an effective shade condition could be found for adjusting the FFMC.

In the daytime, above some level of shading, the correction of T, H, and W to fuel-level conditions should have little or no effect on the fuel moisture prediction. The following method was used to roughly estimate or bound such a threshold. The Alaska black spruce stick data (45 cases) were used with trial threshold values and our adapted model was allowed to completely shade the fuel for cases having shade above the threshold. Effectively, we used a **combination** of two models. By varying the threshold shade used to select the model, we could search for that model-combination (threshold) that reduced the error the most or was optimal in some other sense. As might be expected, the Alaska spruce stick data favored total use of the Canadian FFMC, whose average error was only -0.7%. Other, more open sites, however, favored our model. The shade percentage varied from 50 percent to 95 percent in the Alaska spruce stick data. For trial thresholds below 75 percent, the mean errors (-0.7% to -1.5%) for our new model were comparable to those at other sites. Not wishing to **overpredict** on the other sites, and not wanting to seriously underpredict for Alaska spruce sticks, we set the threshold at a tentative 70 percent. Subsequent validation showed that this allowed the adapted model to perform on all data sets without large mean errors.

APPENDIX D: SUNRISE AND SUNSET DETERMINATION

Referring to figure 3 and equation 4 in the main text, we can solve the equation for the hour-angle (h*) sine:

$$(1)\quad \sinh^* = (\sin A - \sin\phi \sin\delta)/(\cos\phi \cos\delta)$$

where

A = elevation angle of the sun ($-90° \leq A \leq 90°$)

ϕ = latitude

δ = declination $\cong 23.45\ (\sin(0.9863(284+N)))$ (degrees)

N = Julian date

h^* = hour angle from 6 a.m.

We know that the earth's polar axis tilts twice annually to the extent that at the higher latitudes not all the sun-elevation angles (A) are possible. For instance, there may be perpetual day or perpetual night, and no such thing as sunrise (A = o) or sunset (A = o) for long periods. In such cases, equation (1) must not have a solution if it is to be a valid equation. This line of thought leads to the condition

$$(2)\quad -\cos(\delta + \phi) \leq \sin A \leq \cos(\delta - \phi)$$

on δ, ϕ, and A in order for there to be an hour angle (time) for the elevation angle to equal a given A-value.

When condition (2) is satisfied with A = o the hour angles for sunrise and sunset are obtained from equation (1) with

$$\cos h^* = \sqrt{1 - \sin^2 h^*} \quad \text{at sunrise}$$

$$\cos h^* = -\sqrt{1 - \sin^2 h^*} \quad \text{at sunset}$$

This will always be possible if $|\phi| \leq 66.5°$. If $|\phi| \geq 66.5°$, $|\delta|$ must be small enough. The **time** (LST) of the event, in either case, is

$$t = (h^*/15) + 6$$

if h^* is in degrees. Knowing these times and the local standard time, it is easy to determine whether it is day or night and thus apply correct diurnal trends for fuel moisture calculations.

When condition (2) is not satisfied with A = o, we either have perpetual day or perpetual night, and all we need to know is ϕ and δ to determine which:

Perpetual day will occur for

(3) $\phi > 66.5°$ during summer when $\phi + \delta > 90°$ or

(4) $\phi < -66.5°$ during winter when $\phi + \delta < -90°$.

Perpetual night occurs for

(5) $\phi > 66.5°$ during winter when $\phi - \delta > 90°$ or

(6) $\phi < -66.5°$ during summer when $\phi - \delta < -90°$.

This method applies only when condition (2) is violated.

The equation (1) and the condition (2) assume flat terrain and do not account for orbital eccentricities or the "equation of time." A computer program (SUNELT) is available to implement the method described above. By entering the date and the latitude, the user will obtain the times of sunrise and sunset. This program can be obtained by sending a letter and clean tape to Glen Morris, Intermountain Fire Sciences Laboratory, P.O. Box 8069, Missoula, MT 59807.

APPENDIX E: METHODS OF ESTIMATION FOR MISSING MODEL INPUTS

In the initialization section and the diurnal section, it is sometimes necessary for the implementing software to supply missing data. This is done as a convenience to the user who may not always have all the inputs. This appendix explains how it is done.

The model inputs are:

1. m_o = initial 1400-hour fuel moisture
2. $T_1, T_2, \ldots, T_N$ = 1400-hour temperatures for N days
3. $H_1, H_2, \ldots, H_N$ = 1400-hour humidities for N days
4. $W_1, W_2, \ldots, W_N$ = 1400-hour windspeeds for N days
5. $C_1, C_2, \ldots, C_N$ = 1400-hour cloud cover for N days
6. R_o = initial rain amount
7. [T] = diurnal temperature data table
8. [H] = diurnal humidity data table
9. [W] = diurnal wind data table
10. [C] = diurnal cloud cover data table
11. t_p, t_r, t_s = times of projection, sunrise, and sunset
12. Site parameters and the date.

As implemented in the BEHAVE program, the model requires carefully observed values for the mandatory inputs. These are:

1. T_1, T_N, H_1
2. [T], [W], [C]
3. t_p, t_r, t_s
4. Site parameters and the date.

The other values are sometimes "talked in" through the use of categorical descriptors or estimated internally by the model. The model is capable of estimating the following inputs internally

1. m_o
2. $T_2, T_3, \ldots, T_{N-1}$
3. $H_2, H_3, \ldots, H_{N-1}, H_N$.

Internal Estimation of $H_2, H_3, \ldots, H_N$ and Other Humidities

Assuming that the air mass stays constant, we have a constant absolute humidity and therefore a constant dew point (T_d) (Schroeder and Buck 1970). When the model detects that humidity input is missing, it invokes this assumption and computes

$$T_d = -398 - 7469/((ln\ H_i) - 7469/(T_i + 398))\ °F.$$

Under our assumption we can replace T_1 with T_2 in this equation, and solve for H_2. The model does this with all the missing humidities (H_i):

$$H_i = \exp(7469(1/(T_i + 398)) - 1/(T_d + 398)). \quad \text{(E-1)}$$

As long as the air mass is constant and as long as the T_i value is kept current, the estimated humidity (H_i) should be valid.

Equation (E-1) is explained in appendix F and a reference is given there.

Internal Estimation of $T_2, T_3, \ldots, T_{N-1}$

These temperatures, if input as -1°F, are taken to be missing and computed from T_1 and T_N by linear interpolation. This procedure is most likely to work well when day-to-day, 1400-hour temperatures are following a steady trend and not subject to frontal passages (large variations).

Internal Estimation of m_o

At the beginning of a period of days, whatever initial moisture the fuel may have had may be unknown. If the model is given a value of -1 for m_o, it will take this as a signal to estimate m_o using T_1, H_1, W_1, C_1, and R_o. Correcting T_1 and H_1 to fuel level, the model iterates the Canadian Fine Fuel Moisture Code to equilibrium, to obtain the value of fuel moisture (m_o) which would be at equilibrium with T_1 and H_1 at 1400. Now, m_o is meant to represent 1400-hour fuel moisture on the day **before** day 1 of the period of interest. This procedure will be valid enough if

(1) The air mass is constant in such a way that the 1400-hour temperature and humidity were constant, or

(2) The estimation is made sufficiently far in advance of the projection day that errors made in the initial estimate of m_o will have been corrected by subsequent estimates of m with better data (3 days should be adequate).

External Estimation of Missing Inputs

The BEHAVE program queries the user for the inputs it needs and calls our fuel moisture model. As said before, some variables, if unknown, can be "talked in" using categorical descriptors. These are

1. m_o
2. $C_1, C_2, \ldots, C_N$ and [C]
3. R_o.

This procedure is likely to work all right for m_o and R_o if the propagation period length (N) is long (3 or more days). The cloud cover estimates can be very critical near the end of the period when the canopy is sparse. BEHAVE has the ability to ask the user to select one of three categories for each of these inputs.

Wind inputs are not, at this time, talked in, but supplied by the user. Under relatively shaded conditions, windspeed is not critical, and the user can supply a rough estimate—what he believes to be the average value.

APPENDIX F: FORMULA USED FOR HUMIDITY AND DEW POINT CALCULATIONS

The humidity fraction of air is closely approximated by

$$H = e/e_s$$

where

e = vapor pressure

e_s = vapor pressure at saturation.

In order to relate humidity to dew point (T_d) for a given temperature (T), the straightforward approach is to look up equations for e and e_s in terms of T and T_d. But this leads to very cumbersome equations that cannot be easily solved for T_d in terms of T and h.

In Buck (1981), a very handy formula is given for $0 < T(°C) < 50$. This is:

$$ln H = \beta\gamma\,(T_d - T)/(T_d + \gamma)/(T + \gamma) \qquad \text{(F-1)}$$

For temperatures in °F, this becomes

$$ln\ H = 7469(1/(T + 398) - 1/(T_d + 398)).$$

Solving easily now for T_d,

$$T_d = -398 - 7469/((ln\ H) - 7469/(T + 398))\ °F.$$

APPENDIX G: SUMMARY OF VALIDATON DATA

Measured Data

IDAHO FOREST LITTER (FRANDSEN DATA)

ROW	DATE		TIME	TEM-PERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIP-ITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	8	13	14.5	69.0	40.0	*	0.00	3.	14.0
2	8	9	13.0	72.0	33.0	*	0.00	1.	12.0
3	8	9	13.8	66.0	29.0	*	0.00	1.	14.0
4	8	13	13.3	54.0	67.0	*	0.00	3.	15.0
5	9	13	13.8	57.0	36.0	*	0.00	2.	24.0
6	10	9	12.8	44.0	54.0	*	0.00	4.	19.0

ARIZONA PINE NEEDLES (HARRINGTON CLOSED STAND DATA)

ROW	DATE		TIME	TEM-PERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIP-ITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	6	7	14.5	65.0	46.0	8.0	0.00	1.	10.8
2	6	13	15.5	74.0	24.0	5.0	0.00	4.	5.6
3	6	15	14.0	78.0	26.0	5.0	0.00	1.	6.0
4	6	17	15.0	65.0	29.0	40.0	0.03	2.	6.3
5	6	21	13.0	78.0	23.0	2.0	0.00	1.	5.7
6	6	25	15.0	79.0	19.0	5.0	0.00	2.	4.1
7	6	28	13.0	82.0	26.0	5.0	0.00	1.	6.2
8	7	4	14.0	71.0	31.0	10.0	0.03	3.	6.4
9	7	13	13.5	73.0	51.0	5.0	0.00	5.	7.3
10	7	16	13.0	78.0	36.0	12.0	0.00	1.	5.0
11	7	27	15.0	79.0	46.0	1.0	0.00	5.	8.3
12	8	3	14.0	74.0	48.0	5.0	0.00	4.	8.3
13	8	6	15.5	72.0	47.0	1.0	0.00	1.	8.0
14	8	20	13.0	65.0	50.0	5.0	0.00	1.	7.8

ARIZONA PINE STICKS (HARRINGTON CLOSED STAND DATA)

ROW	DATE		TIME	TEM-PERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIP-ITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	6	13	15.5	74.0	24.0	5.0	0.00	4.	8.2
2	6	21	13.0	78.0	23.0	2.0	0.00	1.	7.0
3	7	4	14.0	71.0	31.0	10.0	0.03	3.	7.9
4	7	27	15.0	79.0	46.0	1.0	0.00	5.	13.6
5	8	3	14.0	74.0	48.0	5.0	0.00	4.	9.9
6	8	6	15.5	72.0	47.0	1.0	0.00	1.	9.3

*NOTE -- THE IDAHO DATA HAS NO WINDSPEED MEASUREMENTS. 10 MPH WAS USED FOR THE CASES TABULATED HERE.

(con.)

IDAHO FOREST LITTER (FRANDSEN DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	49.9	14.0	8.3	8.6	9.0	-5.7	-5.4	-5.0
2	31.6	12.0	8.9	10.6	9.0	-3.1	-1.4	-3.0
3	36.3	14.0	10.5	10.3	9.0	-3.5	-3.7	-5.0
4	96.6	15.0	16.5	13.2	13.0	1.5	-1.8	-2.0
5	38.6	24.0	15.7	15.3	10.0	-8.3	-8.7	-14.0
6	76.5	19.0	20.3	11.9	11.0	1.3	-7.1	-8.0

ARIZONA PINE NEEDLES (HARRINGTON CLOSED STAND DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	100.0	10.8	13.1	13.1	10.0	2.3	2.3	-0.8
2	100.0	5.6	8.2	8.2	6.0	2.6	2.6	0.4
3	100.0	6.0	7.0	7.0	7.0	1.0	1.0	1.0
4	100.0	6.3	7.9	7.9	8.0	1.6	1.6	1.7
5	100.0	5.7	6.4	6.4	6.0	0.7	0.7	0.3
6	100.0	4.1	5.2	5.2	5.0	1.1	1.1	0.9
7	100.0	6.2	6.0	6.0	7.0	-0.2	-0.2	0.8
8	100.0	6.4	10.1	10.1	8.0	3.7	3.7	1.6
9	100.0	7.3	9.0	9.0	10.0	1.7	1.7	2.7
10	100.0	5.0	7.5	7.5	8.0	2.5	2.5	3.0
11	100.0	8.3	10.2	10.2	10.0	1.9	1.9	1.7
12	100.0	8.3	11.0	11.0	11.0	2.7	2.7	2.7
13	100.0	8.0	10.3	10.3	11.0	2.3	2.3	3.0
14	100.0	7.8	14.0	14.0	11.0	6.2	6.2	3.2

ARIZONA PINE STICKS (HARRINGTON CLOSED STAND DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	100.0	8.2	8.2	8.2	6.0	0.0	0.0	-2.2
2	100.0	7.0	6.4	6.4	6.0	-0.6	-0.6	-1.0
3	100.0	7.9	10.4	10.4	8.0	2.5	2.5	0.1
4	100.0	13.6	10.1	10.1	10.0	-3.5	-3.5	-3.6
5	100.0	9.9	11.0	11.0	11.0	1.1	1.1	1.1
6	100.0	9.3	11.3	11.3	11.0	2.0	2.0	1.7

(con)

APPENDIX G (Con.)

Measured Data

TEXAS GRASSES (CLARK DATA)

ROW	DATE		TIME	TEM-PERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIP-ITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	3	16	12.3	63.0	36.0	6.6	0.00	1.	15.1
2	3	16	14.1	66.0	31.0	12.0	0.00	1.	9.2
3	3	16	15.3	64.0	34.0	15.6	0.00	1.	12.5
4	4	4	12.2	64.0	35.0	12.9	0.00	1.	5.5
5	4	4	14.6	70.0	22.0	21.4	0.00	1.	4.2
6	4	4	15.2	70.0	21.0	21.5	0.00	1.	4.2
7	4	4	15.8	70.0	19.0	20.4	0.00	1.	4.2
8	2	10	14.0	53.0	41.0	11.8	0.00	1.	6.1
9	2	10	14.4	63.0	32.0	11.8	0.00	1.	5.1
10	2	10	15.3	62.0	33.0	10.2	0.00	1.	5.1
11	2	10	15.8	62.0	35.0	16.8	0.00	1.	5.1
12	4	2	12.0	68.0	25.0	31.4	0.00	1.	3.1
13	4	15	12.5	85.0	16.0	14.2	0.00	1.	3.2
14	4	15	13.7	85.0	12.0	17.4	0.00	1.	3.2
15	4	15	15.6	87.0	12.0	16.5	0.00	1.	3.2
16	3	19	12.6	61.0	26.0	2.9	0.00	1.	12.8
17	3	24	14.3	79.0	27.0	18.8	0.00	1.	21.5
18	3	25	15.1	63.0	57.0	17.4	0.00	1.	13.5
19	4	10	13.9	77.0	61.0	14.9	0.00	1.	20.1
20	4	11	12.4	86.0	49.0	9.5	0.00	1.	11.0
21	3	13	13.2	69.0	31.0	11.4	0.00	1.	6.2
22	3	13	14.3	67.0	34.0	12.2	0.00	1.	6.2
23	3	13	16.0	71.0	33.0	17.9	0.00	1.	6.2
24	3	19	12.6	75.0	21.0	14.8	0.00	1.	6.0
25	3	19	13.0	79.0	20.0	15.8	0.00	1.	5.9
26	3	27	12.3	49.0	81.0	9.9	0.00	1.	15.6
27	3	12	12.0	85.0	18.0	23.8	0.00	1.	1.0
28	3	12	12.8	88.0	14.0	22.7	0.00	1.	1.0
29	3	16	13.5	74.0	24.0	7.2	0.00	1.	4.0
30	4	3	12.1	65.0	25.0	10.2	0.00	1.	3.9
31	4	3	12.3	69.0	25.0	10.9	0.00	1.	3.9

ARIZONA PINE NEEDLES (SACKETT OPEN STAND DATA)

ROW	DATE		TIME	TEM-PERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIP-ITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	5	26	14.4	74.0	21.0	3.0	0.00	1.	4.8
2	6	1	14.0	72.0	22.0	12.0	0.00	1.	5.2
3	6	8	14.0	70.0	23.0	12.0	0.00	1.	4.6
4	6	10	13.5	71.0	24.0	3.0	0.00	1.	7.1
5	6	13	14.8	69.0	16.0	10.0	0.00	1.	3.9
6	6	15	14.3	74.0	11.0	7.0	0.00	1.	2.9
7	6	17	14.5	79.0	16.0	12.0	0.00	1.	3.4
8	6	22	13.8	76.0	18.0	5.0	0.00	1.	3.1
9	6	29	13.7	78.0	15.0	12.0	0.00	2.	2.7
10	7	6	13.1	82.0	23.0	10.0	0.00	1.	2.6
11	7	8	13.2	72.0	46.0	3.0	0.00	1.	9.9
12	7	11	14.8	81.0	22.0	3.0	0.00	1.	4.2
13	7	13	14.1	80.0	17.0	7.0	0.00	1.	4.0
14	7	20	13.0	70.0	38.0	5.0	0.00	2.	6.5
15	7	27	14.0	74.0	40.0	11.0	0.00	1.	7.8
16	7	29	13.5	77.0	32.0	8.0	0.00	1.	4.7
17	8	1	14.0	66.0	65.0	3.0	0.00	1.	9.0
18	8	5	14.0	82.0	33.0	3.0	0.00	2.	4.5
19	8	19	13.7	64.0	60.0	3.0	0.00	1.	10.8

(con)

TEXAS GRASSES (CLARK DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	54.0	15.1	10.2	11.3	10.0	-4.9	-3.8	-5.1
2	51.0	9.2	9.1	9.9	9.0	-0.1	0.7	-0.2
3	42.0	12.5	9.9	10.7	6.0	-2.6	-1.8	-6.5
4	15.0	5.5	5.7	10.9	7.0	0.2	5.4	1.5
5	5.0	4.2	4.7	7.7	5.0	0.5	3.5	0.8
6	0.0	4.2	4.5	7.5	5.0	0.3	3.3	0.8
7	0.0	4.2	4.6	7.0	4.0	0.4	2.8	-0.2
8	0.0	6.1	8.2	13.1	7.0	2.1	7.0	0.9
9	0.0	5.1	5.6	10.3	6.0	0.5	5.2	0.9
10	0.0	5.1	6.3	10.6	6.0	1.2	5.5	0.9
11	0.0	5.1	8.6	11.0	7.0	3.5	5.9	1.9
12	37.0	3.1	7.6	8.5	6.0	4.5	5.4	2.9
13	22.0	3.2	4.2	4.9	3.0	1.0	1.7	-0.2
14	13.0	3.2	3.6	4.3	3.0	0.4	1.1	-0.2
15	0.0	3.2	3.4	4.3	3.0	0.2	1.1	-0.2
16	9.0	12.8	3.9	9.1	6.0	-8.9	-3.7	-6.8
17	22.0	21.5	5.6	7.2	5.0	-15.9	-14.3	-16.5
18	0.0	13.5	9.2	15.6	9.0	-4.3	2.1	-4.5
19	87.0	20.1	13.3	13.3	12.0	-6.8	-6.8	-8.1
20	18.0	11.0	6.3	10.5	8.0	-4.7	-0.5	-3.0
21	67.0	6.2	9.5	9.8	9.0	3.3	3.6	2.8
22	49.0	6.2	9.8	10.6	6.0	3.6	4.4	-0.2
23	11.0	6.2	7.5	8.7	7.0	1.3	2.5	0.8
24	26.0	6.0	4.7	6.1	4.0	-1.3	0.1	-2.0
25	21.0	5.9	4.4	5.8	4.0	-1.5	-0.1	-1.9
26	80.0	15.6	25.9	25.9	15.0	10.3	10.3	-0.6
27	22.0	1.0	4.2	5.3	4.0	3.2	4.3	3.0
28	4.0	1.0	3.9	4.5	3.0	2.9	3.5	2.0
29	10.0	4.0	4.2	6.7	4.0	0.2	2.7	0.0
30	20.0	3.9	4.3	8.6	6.0	0.4	4.7	2.1
31	29.0	3.9	4.9	8.4	6.0	1.0	4.5	2.1

ARIZONA PINE NEEDLES (SACKETT OPEN STAND DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	90.4	4.8	6.1	6.1	6.0	1.3	1.3	1.2
2	14.0	5.2	4.2	6.4	3.0	-1.0	1.2	-2.2
3	33.1	4.6	4.5	7.9	3.0	-0.2	3.3	-1.6
4	71.3	7.1	8.1	8.1	6.0	1.0	1.0	-1.1
5	4.4	3.9	3.6	6.2	3.0	-0.3	2.3	-0.9
6	14.0	2.9	2.7	4.8	2.0	-0.1	1.9	-0.9
7	52.2	3.4	4.3	4.9	5.0	1.0	1.6	1.6
8	61.8	3.1	3.8	4.2	5.0	0.7	1.0	1.9
9	9.2	2.7	3.1	4.2	2.0	0.4	1.5	-0.7
10	52.2	2.6	5.0	6.3	6.0	2.4	3.6	3.4
11	90.4	9.9	11.1	11.1	10.0	1.2	1.2	0.1
12	42.6	4.2	4.4	6.1	3.0	0.3	2.0	-1.2
13	42.6	4.0	4.2	5.1	2.0	0.2	1.2	-2.0
14	66.5	6.5	7.0	7.6	8.0	0.5	1.1	1.5
15	52.2	7.8	9.4	10.0	9.0	1.5	2.1	1.2
16	80.9	4.7	8.2	8.2	8.0	3.5	3.5	3.3
17	100.0	9.0	17.0	17.0	13.0	7.9	7.9	4.0
18	37.9	4.5	5.9	10.2	6.0	1.3	5.6	1.5
19	100.0	10.8	16.2	16.2	12.0	5.4	5.4	1.2

(con.)

APPENDIX G (Con.)

Measured Data

ALASKA SPRUCE STICKS (NORUM DATA)

ROW	DATE		TIME	TEMPERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIPITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	6	20	13.5	60.0	49.0	0.0	0.00	1.	19.3
2	7	23	14.4	75.0	41.0	3.7	0.00	1.	9.1
3	6	28	12.6	65.0	48.0	4.3	0.00	1.	13.3
4	8	1	15.6	62.0	42.0	5.4	0.00	1.	9.2
5	6	19	14.2	52.0	75.0	2.6	0.00	1.	13.6
6	8	1	13.9	64.0	39.0	2.7	0.00	1.	15.4
7	8	13	12.5	73.0	46.0	2.5	0.00	1.	11.9
8	7	24	14.2	82.0	37.0	6.8	0.00	1.	8.5
9	8	3	12.7	67.0	31.0	5.0	0.00	1.	10.6
10	8	13	15.0	77.0	42.0	5.3	0.00	1.	14.4
11	5	25	13.0	58.0	42.0	0.0	0.00	1.	11.1
12	5	27	13.0	60.0	44.0	0.0	0.00	1.	21.5
13	6	16	14.1	54.0	45.0	0.0	0.00	1.	11.0
14	7	2	13.8	69.0	51.0	0.0	0.00	1.	10.7
15	7	23	12.0	76.0	39.0	0.0	0.00	1.	25.0
16	6	15	12.3	59.0	48.0	0.0	0.00	1.	11.3
17	7	25	12.7	77.0	43.0	0.0	0.00	1.	8.5
18	6	15	13.2	59.0	48.0	0.0	0.00	1.	18.1
19	6	19	13.4	56.0	50.0	0.0	0.00	1.	16.4
20	6	25	14.1	59.0	58.0	0.0	0.00	1.	16.6
21	7	23	13.6	76.0	32.0	0.0	0.00	1.	15.6
22	7	22	15.8	84.0	35.0	0.0	0.00	1.	19.8
23	7	24	15.0	59.0	73.0	0.0	0.00	1.	7.4
24	7	30	13.0	68.0	43.0	0.0	0.00	1.	17.3

Measured Data

ALASKA HARDWOOD STICKS (NORUM DATA)

ROW	DATE		TIME	TEMPERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIPITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	6	20	12.8	56.0	55.0	0.0	0.00	1.	19.5
2	7	23	13.7	74.0	40.0	2.2	0.00	1.	18.2
3	7	25	12.1	73.0	36.0	1.6	0.00	1.	17.4
4	6	20	15.0	57.0	53.0	6.4	0.00	1.	15.1
5	7	20	15.2	71.0	53.0	0.0	0.00	1.	14.1
6	5	30	13.8	55.0	49.0	0.0	0.00	1.	9.6
7	6	19	13.5	50.0	56.0	0.0	0.00	1.	10.7
8	8	1	14.5	68.0	35.0	0.0	0.00	1.	10.7
9	8	13	12.1	73.0	46.0	0.0	0.00	1.	7.5
10	5	29	12.3	68.0	39.0	0.0	0.00	1.	10.3
11	6	19	15.8	61.0	45.0	0.0	0.00	1.	11.6
12	7	24	12.4	77.0	43.0	3.0	0.00	1.	7.5
13	8	3	13.3	64.0	48.0	3.3	0.00	1.	9.6
14	8	13	15.7	78.0	43.0	5.3	0.00	1.	6.8
15	6	8	14.7	68.0	28.0	2.7	0.00	1.	22.2
16	6	11	15.2	67.0	34.0	2.5	0.24	3.	17.9
17	6	15	12.1	70.0	51.0	2.4	0.03	4.	15.1
18	6	22	14.2	60.0	68.0	2.2	0.05	7.	12.7
19	6	24	14.2	71.0	34.0	2.5	0.00	2.	11.5
20	7	28	14.3	68.0	51.0	1.3	0.00	1.	25.1
21	8	8	12.1	68.0	51.0	0.5	0.00	5.	26.9
22	6	11	14.2	66.0	33.0	0.6	0.17	3.	20.6
23	6	20	14.3	67.0	48.0	1.8	0.10	5.	13.6
24	6	24	15.0	73.0	36.0	1.1	0.05	4.	11.9
25	5	31	12.8	62.0	69.0	2.3	0.00	2.	15.4
26	6	8	13.7	68.0	28.0	3.2	0.02	3.	9.8
27	6	15	13.2	73.0	40.0	1.4	0.00	2.	11.2
28	6	20	13.2	64.0	52.0	0.3	0.02	5.	10.6
29	6	24	13.3	70.0	34.0	1.8	0.00	2.	10.1
30	7	4	14.0	60.0	33.0	3.8	0.00	3.	18.2
31	8	8	15.3	68.0	51.0	0.3	0.00	5.	26.5
32	6	3	14.0	48.0	51.0	4.1	0.00	1.	25.5
33	6	5	12.6	60.0	40.0	1.2	0.02	2.	28.1
34	6	11	12.5	68.0	33.0	3.6	0.09	3.	17.4
35	6	14	13.1	72.0	40.0	0.0	0.15	3.	15.1
36	6	20	12.1	65.0	53.0	1.9	0.09	6.	11.9
37	6	24	12.3	66.0	41.0	0.8	0.04	2.	16.1

(con.)

Prediction

ALASKA SPRUCE STICKS (NORUM DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	91.0	19.3	14.5	14.5	10.0	-4.8	-4.8	-9.3
2	84.0	9.1	10.0	10.0	9.0	0.9	0.9	-0.1
3	97.0	13.3	13.6	13.6	10.0	0.3	0.3	-3.3
4	73.0	9.2	12.6	12.6	10.0	3.4	3.4	0.8
5	73.0	13.6	23.2	23.2	13.0	9.6	9.6	-0.6
6	52.0	15.4	11.8	11.8	10.0	-3.6	-3.6	-5.4
7	73.0	11.9	11.1	11.1	11.0	-0.8	-0.8	-0.9
8	100.0	8.5	8.8	8.8	8.0	0.3	0.3	-0.5
9	73.0	10.6	9.9	9.9	9.0	-0.7	-0.7	-1.6
10	73.0	14.4	10.0	10.0	10.0	-4.4	-4.4	-4.4
11	97.0	11.1	13.1	13.1	9.0	2.0	2.0	-2.1
12	73.0	21.5	13.3	13.3	9.0	-8.2	-8.2	-12.5
13	73.0	11.0	14.3	14.3	10.0	3.3	3.3	-1.0
14	73.0	10.7	13.8	13.8	10.0	3.1	3.1	-0.7
15	52.0	25.0	8.5	9.5	8.0	-16.5	-15.5	-17.0
16	73.0	11.3	14.4	14.4	10.0	3.1	3.1	-1.3
17	73.0	8.5	10.2	10.2	9.0	1.7	1.7	0.5
18	73.0	18.1	14.4	14.4	10.0	-3.7	-3.7	-8.1
19	97.0	16.4	15.2	15.2	10.0	-1.2	-1.2	-6.4
20	73.0	16.6	16.7	16.7	11.0	0.1	0.1	-5.6
21	43.0	15.6	7.8	8.2	8.0	-7.8	-7.4	-7.6
22	52.0	19.8	8.4	8.4	8.0	-11.4	-11.4	-11.8
23	97.0	7.4	20.8	20.8	12.0	13.4	13.4	4.6
24	73.0	17.3	12.3	12.3	9.0	-4.9	-4.9	-8.3

Prediction

ALASKA HARDWOOD STICKS (NORUM DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	88.8	19.5	16.5	16.5	11.0	-3.0	-3.0	-8.5
2	80.0	18.2	9.9	9.9	9.0	-8.3	-8.3	-9.2
3	80.0	17.4	9.2	9.2	8.0	-8.3	-8.3	-9.4
4	96.3	15.1	15.5	15.5	10.0	0.4	0.4	-5.1
5	66.3	14.1	12.5	12.5	10.0	-1.6	-1.6	-4.1
6	98.8	9.6	15.1	15.1	10.0	5.5	5.5	0.4
7	88.8	10.7	17.9	17.9	11.0	7.2	7.2	0.3
8	80.0	10.7	10.7	10.7	10.0	0.0	0.0	-0.7
9	88.8	7.5	11.0	11.0	11.0	3.5	3.5	3.5
10	98.8	10.3	11.5	11.5	9.0	1.3	1.3	-1.3
11	88.8	11.6	13.4	13.4	10.0	1.8	1.8	-1.6
12	88.8	7.5	10.2	10.2	9.0	2.7	2.7	1.5
13	88.8	9.6	13.7	13.7	11.0	4.1	4.1	1.4
14	88.8	6.8	10.1	10.1	10.0	3.3	3.3	3.2
15	99.3	22.2	18.5	18.5	8.0	-3.7	-3.7	-14.2
16	91.5	17.9	13.6	13.6	8.0	-4.3	-4.3	-9.9
17	89.3	15.1	11.1	11.1	10.0	-4.0	-4.0	-5.1
18	91.5	12.7	13.7	13.7	12.0	1.0	1.0	-0.7
19	88.0	11.5	10.1	10.1	8.0	-1.4	-1.4	-3.5
20	93.3	25.1	27.8	27.8	10.0	2.6	2.6	-15.1
21	95.8	26.9	15.2	15.2	11.0	-11.6	-11.6	-15.9
22	94.3	20.6	15.6	15.6	8.0	-5.0	-5.0	-12.6
23	93.9	13.6	9.8	9.8	10.0	-3.8	-3.8	-3.6
24	93.8	11.9	11.4	11.4	8.0	-0.5	-0.5	-3.9
25	93.6	15.4	20.4	20.4	12.0	5.0	5.0	-3.4
26	93.5	9.8	9.8	9.8	8.0	0.1	0.1	-1.8
27	86.9	11.2	10.1	10.1	9.0	-1.1	-1.1	-2.2
28	89.9	10.6	10.1	10.1	10.0	-0.6	-0.6	-0.6
29	88.0	10.1	10.7	10.7	8.0	0.6	0.6	-2.1
30	89.8	18.2	13.8	13.8	8.0	-4.3	-4.3	-10.2
31	93.4	26.5	14.7	14.7	11.0	-11.8	-11.8	-15.5
32	98.3	25.5	27.0	27.0	10.0	1.5	1.5	-15.5
33	78.1	28.1	16.4	16.4	9.0	-11.8	-11.8	-19.1
34	83.1	17.4	13.7	13.7	8.0	-3.7	-3.7	-9.4
35	76.1	15.1	14.5	14.5	9.0	-0.6	-0.6	-6.1
36	75.8	11.9	11.0	11.0	10.0	-1.0	-1.0	-1.9
37	72.0	16.1	12.3	12.3	9.0	-3.8	-3.8	-7.1

(con.)

APPENDIX G (Con.)

Measured Data

ALASKA LEAF LITTER (NORUM DATA)

ROW	DATE		TIME	TEMPERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIPITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	6	20	12.8	56.0	55.0	0.0	0.00	1.	24.5
2	7	23	13.7	74.0	40.0	2.2	0.00	1.	12.7
3	7	25	12.1	73.0	36.0	1.6	0.00	1.	15.8
4	6	20	15.0	57.0	53.0	6.4	0.00	1.	17.6
5	7	20	15.2	71.0	53.0	0.0	0.00	1.	10.7
6	5	30	13.8	55.0	49.0	0.0	0.00	1.	16.6
7	6	19	13.5	50.0	56.0	0.0	0.00	1.	15.2
8	8	1	14.5	68.0	35.0	0.0	0.00	1.	9.9
9	8	13	12.1	73.0	46.0	0.0	0.00	1.	9.3
10	5	29	12.3	68.0	39.0	0.0	0.00	1.	12.7
11	6	19	15.8	61.0	45.0	0.0	0.00	1.	10.0
12	7	24	12.4	77.0	43.0	3.0	0.00	1.	7.2
13	8	3	13.3	64.0	48.0	3.3	0.00	1.	10.6
14	8	13	15.7	78.0	43.0	5.3	0.00	1.	8.6
15	6	8	14.7	68.0	28.0	2.7	0.00	1.	14.9
16	6	11	15.2	67.0	34.0	2.5	0.24	3.	17.2
17	6	15	12.1	70.0	51.0	2.4	0.03	4.	17.2
18	6	22	14.2	60.0	68.0	2.2	0.05	7.	17.1
19	6	24	14.2	71.0	34.0	2.5	0.00	2.	12.9
20	7	25	14.8	67.0	63.0	0.4	0.00	1.	23.3
21	7	28	14.3	68.0	51.0	1.3	0.00	1.	28.4
22	8	18	14.0	59.0	34.0	0.0	0.00	1.	29.5
23	6	3	12.4	49.0	43.0	0.8	0.00	1.	24.7
24	6	11	14.2	66.0	33.0	0.6	0.00	1.	17.7
25	6	20	14.3	67.0	48.0	1.8	0.10	5.	18.0
26	6	24	15.0	73.0	36.0	1.1	0.05	4.	12.6
27	7	4	12.4	60.0	40.0	5.0	0.00	3.	26.9
28	7	28	15.0	68.0	55.0	0.0	0.00	1.	21.2
29	5	31	12.8	62.0	69.0	2.3	0.00	2.	16.3
30	6	8	13.7	68.0	28.0	3.2	0.02	3.	12.3
31	6	15	13.2	73.0	40.0	1.4	0.00	2.	13.6
32	6	20	13.2	64.0	52.0	0.3	0.02	5.	13.6
33	6	24	13.3	70.0	34.0	1.8	0.00	2.	11.2
34	7	4	14.0	60.0	33.0	3.8	0.00	3.	16.6
35	8	8	15.3	68.0	51.0	0.3	0.00	5.	20.5
36	8	18	12.4	53.0	45.0	1.2	0.00	1.	26.9
37	6	3	14.0	48.0	51.0	4.1	0.00	1.	17.9
38	6	5	12.6	60.0	40.0	1.2	0.02	2.	13.4
39	6	8	12.4	63.0	30.0	1.3	0.00	1.	12.8
40	6	11	12.5	68.0	33.0	3.6	0.09	3.	12.3
41	6	14	13.1	72.0	40.0	0.0	0.15	3.	10.4
42	6	20	12.1	65.0	53.0	1.9	0.09	6.	12.1
43	6	24	12.3	66.0	41.0	0.8	0.04	2.	12.7
44	7	3	13.9	58.0	47.0	3.5	0.03	2.	17.3
45	7	25	13.3	68.0	57.0	2.5	0.00	1.	21.3
46	7	28	12.3	68.0	51.0	1.8	0.00	1.	19.5
47	8	8	13.4	68.0	59.0	1.0	0.00	5.	17.3

(con.)

Prediction

ALASKA LEAF LITTER (NORUM DATA)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	88.8	24.5	16.5	16.5	11.0	-8.0	-8.0	-13.5
2	80.0	12.7	9.9	9.9	9.0	-2.8	-2.8	-3.7
3	80.0	15.8	9.2	9.2	8.0	-6.6	-6.6	-7.8
4	96.3	17.6	15.5	15.5	10.0	-2.1	-2.1	-7.6
5	66.3	10.7	12.5	12.5	10.0	1.8	1.8	-0.7
6	98.8	16.6	15.1	15.1	10.0	-1.4	-1.4	-6.6
7	88.8	15.2	17.9	17.9	11.0	2.7	2.7	-4.2
8	80.0	9.9	10.7	10.7	10.0	0.8	0.8	0.1
9	88.8	9.3	11.0	11.0	11.0	1.7	1.7	1.7
10	98.8	12.7	11.5	11.5	9.0	-1.2	-1.2	-3.7
11	88.8	10.0	13.4	13.4	10.0	3.4	3.4	0.0
12	88.8	7.2	10.2	10.2	9.0	3.0	3.0	1.8
13	88.8	10.6	13.7	13.7	11.0	3.1	3.1	0.4
14	88.8	8.6	10.1	10.1	10.0	1.5	1.5	1.4
15	99.3	14.9	37.5	37.5	8.0	22.6	22.6	-6.9
16	91.5	17.2	13.5	13.5	8.0	-3.7	-3.7	-9.2
17	89.3	17.2	11.1	11.1	10.0	-6.1	-6.1	-7.2
18	91.5	17.1	13.7	13.7	12.0	-3.4	-3.4	-5.1
19	88.0	12.9	10.7	10.7	8.0	-2.2	-2.2	-4.9
20	93.3	23.3	37.2	37.2	11.0	13.9	13.9	-12.3
21	93.3	28.4	45.0	45.0	10.0	16.6	16.6	-18.4
22	88.0	29.5	11.1	11.1	9.0	-18.3	-18.3	-20.5
23	99.5	24.7	21.7	21.7	10.0	-3.0	-3.0	-14.7
24	95.5	17.7	15.1	15.1	8.0	-2.6	-2.6	-9.7
25	93.9	18.0	9.8	9.8	10.0	-8.2	-8.2	-8.0
26	93.8	12.6	11.5	11.5	8.0	-1.1	-1.1	-4.6
27	95.5	26.9	21.5	21.5	9.0	-5.4	-5.4	-17.9
28	99.5	21.2	43.4	43.4	11.0	22.2	22.2	-10.2
29	93.6	16.3	20.1	20.1	12.0	3.9	3.9	-4.3
30	93.5	12.3	10.1	10.1	8.0	-2.2	-2.2	-4.3
31	86.9	13.6	11.3	11.3	9.0	-2.4	-2.4	-4.6
32	89.9	13.6	10.1	10.1	10.0	-3.5	-3.5	-3.6
33	88.0	11.2	11.6	11.6	8.0	0.4	0.4	-3.2
34	89.8	16.6	19.3	19.3	8.0	2.7	2.7	-8.6
35	93.4	20.5	14.5	14.5	11.0	-6.0	-6.0	-9.5
36	99.3	26.9	34.2	34.2	11.0	7.3	7.3	-15.9
37	98.3	17.9	20.1	20.1	10.0	2.2	2.2	-7.9
38	78.1	13.4	14.7	14.7	9.0	1.3	1.3	-4.4
39	72.0	12.8	11.2	11.2	8.0	-1.7	-1.7	-4.8
40	83.1	12.3	13.1	13.1	8.0	0.8	0.8	-4.3
41	76.1	10.4	14.4	14.4	9.0	4.0	4.0	-1.4
42	75.8	12.1	10.9	10.9	10.0	-1.1	-1.1	-2.1
43	72.0	12.7	12.1	12.1	9.0	-0.6	-0.6	-3.7
44	78.1	17.3	27.4	27.4	10.0	10.1	10.1	-7.3
45	64.3	21.3	15.9	15.9	11.0	-5.5	-5.5	-10.3
46	98.3	19.5	22.9	22.9	10.0	3.4	3.4	-9.5
47	90.2	17.3	13.6	13.6	12.0	-3.7	-3.7	-5.3

(con.)

APPENDIX G (Con.)

Measured Data

ARIZONA PINE NEEDLES (SACKETT DATA, CLOSURE=74%)

ROW	DATE		TIME	TEM-PERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIP-ITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	5	26	14.4	74.0	21.0	3.0	0.00	1.	5.4
2	6	1	14.0	72.0	22.0	12.0	0.00	1.	4.4
3	6	8	14.0	70.0	23.0	12.0	0.00	1.	3.7
4	6	10	13.5	71.0	24.0	3.0	0.00	1.	9.2
5	6	13	14.8	69.0	16.0	10.0	0.00	1.	3.8
6	6	15	14.3	74.0	11.0	7.0	0.00	1.	4.2
7	6	17	14.5	79.0	16.0	12.0	0.00	1.	3.1
8	6	22	13.8	76.0	18.0	5.0	0.00	1.	3.8
9	6	29	13.7	78.0	15.0	12.0	0.00	2.	2.8
10	7	6	13.1	82.0	23.0	10.0	0.00	1.	3.9
11	7	8	13.2	72.0	46.0	3.0	0.00	1.	15.6
12	7	11	14.8	81.0	22.0	3.0	0.00	1.	6.1
13	7	13	14.1	80.0	17.0	7.0	0.00	1.	5.1
14	7	20	13.0	70.0	38.0	5.0	0.00	2.	4.4
15	7	27	14.0	74.0	40.0	11.0	0.00	1.	9.5
16	7	29	13.5	77.0	32.0	8.0	0.00	1.	5.7
17	8	1	14.0	66.0	65.0	3.0	0.00	1.	9.6
18	8	5	14.0	82.0	33.0	3.0	0.00	2.	6.5
19	8	19	13.7	64.0	60.0	3.0	0.00	1.	17.9

ARIZONA PINE NEEDLES (SACKETT DATA, CLOSURE=94%)

ROW	DATE		TIME	TEM-PERATURE	HUMIDITY	20-FOOT WINDSPEED	PRECIP-ITATION	PERIOD LENGTH	FUEL MOISTURE
	MO	DAY	(HOURS)	(DEG F)	(PCNT)	(MPH)	(IN)	(DAYS)	(PCNT)
1	5	26	14.4	74.0	21.0	3.0	0.00	1.	6.5
2	6	1	14.0	72.0	22.0	12.0	0.00	1.	4.5
3	6	8	14.0	70.0	23.0	12.0	0.00	1.	4.3
4	6	10	13.5	71.0	24.0	3.0	0.00	1.	10.6
5	6	13	14.8	69.0	16.0	10.0	0.00	1.	5.0
6	6	15	14.3	74.0	11.0	7.0	0.00	1.	3.8
7	6	17	14.5	79.0	16.0	12.0	0.00	1.	4.4
8	6	22	13.8	76.0	18.0	5.0	0.00	1.	4.0
9	6	29	13.7	78.0	15.0	12.0	0.00	2.	3.5
10	7	6	13.1	82.0	23.0	10.0	0.00	1.	3.8
11	7	8	13.2	72.0	46.0	3.0	0.00	1.	24.5
12	7	11	14.8	81.0	22.0	3.0	0.00	1.	6.2
13	7	13	14.1	80.0	17.0	7.0	0.00	1.	5.9
14	7	20	13.0	70.0	38.0	5.0	0.00	2.	5.5
15	7	27	14.0	74.0	40.0	11.0	0.00	1.	10.3
16	7	29	13.5	77.0	32.0	8.0	0.00	1.	7.4
17	8	1	14.0	66.0	65.0	3.0	0.00	1.	13.3
18	8	5	14.0	82.0	33.0	3.0	0.00	2.	6.0
19	8	19	13.7	64.0	60.0	3.0	0.00	1.	17.3

(con.)

Prediction

ARIZONA PINE NEEDLES (SACKETT DATA, CLOSURE=74%)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	97.4	5.4	6.1	6.1	6.0	0.7	0.7	0.6
2	76.6	4.4	6.4	6.4	6.0	1.9	1.9	1.6
3	81.8	3.7	7.9	7.9	6.0	4.2	4.2	2.3
4	92.2	9.2	8.1	8.1	6.0	-1.1	-1.1	-3.2
5	74.0	3.8	6.2	6.2	6.0	2.4	2.4	2.2
6	76.6	4.2	4.8	4.8	5.0	0.6	0.6	0.8
7	87.0	3.1	4.9	4.9	5.0	1.8	1.8	1.9
8	89.6	3.8	4.5	4.5	5.0	0.7	0.7	1.2
9	75.3	2.8	4.1	4.1	5.0	1.3	1.3	2.2
10	87.0	3.9	6.3	6.3	6.0	2.4	2.4	2.1
11	97.4	15.6	11.1	11.1	10.0	-4.5	-4.5	-5.6
12	84.4	6.1	6.1	6.1	6.0	0.0	0.0	-0.1
13	84.4	5.1	5.1	5.1	5.0	0.0	0.0	-0.1
14	90.9	4.4	7.5	7.5	8.0	3.2	3.2	3.6
15	87.0	9.5	12.2	12.2	9.0	2.7	2.7	-0.5
16	94.8	5.7	8.2	8.2	8.0	2.5	2.5	2.3
17	100.0	9.6	17.0	17.0	13.0	7.3	7.3	3.4
18	83.1	6.5	10.7	10.7	9.0	4.2	4.2	2.5
19	100.0	17.9	16.2	16.2	12.0	-1.7	-1.7	-5.9

ARIZONA PINE NEEDLES (SACKETT DATA, CLOSURE=94%)

ROW	SHADE	FUEL MOISTURE (PCNT)				ERROR		
		ACTUAL	BEHAVE	FFMC	FBO	BEHAVE	FFMC	FBO
1	99.4	6.5	6.1	6.1	6.0	-0.4	-0.4	-0.5
2	94.6	4.5	6.4	6.4	6.0	1.9	1.9	1.5
3	95.8	4.3	7.9	7.9	6.0	3.7	3.7	1.8
4	98.2	10.6	8.1	8.1	6.0	-2.6	-2.6	-4.6
5	94.0	5.0	6.2	6.2	6.0	1.2	1.2	1.0
6	94.6	3.8	4.8	4.8	5.0	1.0	1.0	1.2
7	97.0	4.4	4.9	4.9	5.0	0.6	0.6	0.6
8	97.6	4.0	4.4	4.4	5.0	0.4	0.4	1.0
9	94.3	3.5	4.3	4.3	5.0	0.8	0.8	1.5
10	97.0	3.8	6.3	6.3	6.0	2.5	2.5	2.2
11	99.4	24.5	11.1	11.1	10.0	-13.4	-13.4	-14.5
12	96.4	6.2	6.1	6.1	6.0	-0.1	-0.1	-0.2
13	96.4	5.9	5.1	5.1	5.0	-0.8	-0.8	-0.9
14	97.9	5.5	7.8	7.8	8.0	2.3	2.3	2.5
15	97.0	10.3	13.1	13.1	9.0	2.8	2.8	-1.3
16	98.8	7.4	8.2	8.2	8.0	0.8	0.8	0.6
17	100.0	13.3	17.0	17.0	13.0	3.7	3.7	-0.3
18	96.1	6.0	11.1	11.1	9.0	5.1	5.1	3.0
19	100.0	17.3	16.2	16.2	12.0	-1.1	-1.1	-5.3

☆ U.S. GOVERNMENT PRINTING OFFICE: 1986-676-039/20037

Rothermel, Richard C.; Wilson, Ralph A.; Morris, Glen A.; Sackett, Stephen S. Modeling moisture content of fine dead wildland fuels: input to the BEHAVE fire prediction system. Research Paper INT-359. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986 61 p.

Describes a model for predicting moisture content of fine fuels for use with the BEHAVE fire behavior and fuel modeling system. The model is intended to meet the need for more accurate predictions of fine fuel moisture, particularly in northern conifer stands and on days following rain. The model is based on the Canadian Fine Fuel Moisture Code (FFMC), modified to account for solar heating of fuels and to predict diurnal trends in fine fuel moisture. The model may be initiated without extensive data on prior weather. When compared to the FFMC and the fire behavior officers' procedures, the new model gave consistently better predictions over the complete range of fuel conditions.

KEYWORDS: fuel moisture, fine fuels, model, fire behavior, diurnal, solar, shade

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

A 13.78: Int - Research Paper no. 360 is available on microfiche which is located in microfiche cabinets on third floor.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station
Ogden, UT 84401**

Research Paper
INT-361

January 1986

Four Analytical Approaches for Integrating Land Management and Transportation Planning on Forest Lands

**J. Greg Jones
James F. C. Hyde, III
Mary L. Meacham**

THE AUTHORS

J. GREG JONES is a research forester with the Economics Research Work Unit, Forestry Sciences Laboratory, Missoula, MT. His research includes economic efficiency modeling for use in multiple-use management, measurement of multiple-use costs, and analysis of economic impact. He received his Ph.D. in forest economics from Iowa State University in 1976.

JAMES F. C. HYDE, III is an economist with the Economics Research Work Unit in Missoula, MT. His research includes topics in forest planning, resource economics, and allocative efficiency. He is a graduate of the University of Montana.

MARY L. MEACHAM is a statistician with the Economics Research Work Unit, Forestry Sciences Laboratory, Missoula, MT. Her research includes work in mathematical programming, regression analysis, and other statistical techniques. She is a graduate of the University of Montana.

ACKNOWLEDGMENTS

Numerous Forest Service offices participated in this study. Foresters, engineers, and resource specialists on the Lolo, Kootenai, and Clearwater National Forests provided the data for the approaches and selected the harvesting and road construction activities for the simulations. Although many people were involved, several individuals on each Forest played particularly key roles: Douglas Berglund, Earl Sutton, and Wayne Johnson (Lolo NF); Jerrold Park, Robert Wetzel, and Joseph Lewicki (Kootenai NF); and Maurice Pare, Ed Butler, and Richard Patten (Clearwater NF). Also, the Engineering, Timber Management, Program Planning and Budgeting, and Management Systems staffs in the Northern Region headquarters provided valuable support and guidance in the design and completion of this study. Key roles here were played by Charles Burley, Dayton Nelson, William Schnelle, and David Wright. Finally, Peter Wong and Malcolm Kirby of the Forest Service Management Science Staff at Berkeley, CA, provided valuable assistance in the operation of the Integrated Resources Planning Model software used in this study.

CONTENTS

	Page
Introduction	1
Developing a Basic Formulation for ALA	2
Delineating Land Area	2
Timber Management Projects	2
Potential Transportation Network	3
Road Construction Projects	3
Analysis Approaches Tested	3
Testing Analytical Approaches	4
Test Areas	4
Summary of Data Used	8
Comparing Approaches	10
Modeling Procedures	10
Results and Discussion	12
DNR Comparisons	13
Differences in Other Factors	16
Required Resources	30
Conclusions	31
References	33

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

RESEARCH SUMMARY

When and where to harvest timber and construct roads on a site-specific basis must be decided when implementing forest plans. Many managers believe that such decisions are best made using an integrated, area-level analysis, applied on contiguous areas 5,000 to 50,000 acres in size. This analysis would focus on the efficiency of harvesting practices and road construction patterns (location, timing, design) and environmental impacts over time.

This paper compares four "generic" analytical approaches for use in area-level analysis:

1. **Fixed-access simulation (FX).**—In the FX approach, the analyst or manager decides how each potential harvesting unit is to be accessed prior to any analysis. These routes are locked in (fixed) and cannot be altered for the rest of the analysis. Therefore, under this simulation approach, the analyst only decides which units to harvest and when the harvesting should take place.

2. **Variable-access simulation (VR).**—As in the FX approach, the analyst decides how each potential harvesting unit is to be accessed. In the VR approach, however, these routes can be changed at any time during the analysis. Therefore, the analyst chooses which units to harvest, when to harvest, and how each of those units is accessed.

3. **Simulation with minimization of road costs (MC).**—The MC approach also requires the analyst or manager to select the units to harvest and the timing of the activity. This approach then utilizes an optimization routine to determine the least cost transportation plan (sum of discounted road construction, reconstruction, haul and maintenance costs) for accessing those units.

4. **Optimization (MX).**—The MX approach simultaneously selects the combination of harvest and road construction activities which maximizes or minimizes a specified objective function while satisfying other management objectives. In this approach there are no choices for the analyst or manager to make regarding harvest or road construction activities.

Each of the approaches was tested twice (Series I and II) on three actual planning areas selected to provide a range of conditions typical of the Northern Rocky Mountains. Data, including yields, costs, and prices, as well as the site-specific harvesting and road construction activities, were furnished by cooperating National Forest System personnel. The same data were used in each approach. In each series, each approach was to identify the combination of harvest and road construction activities over a 50-year period that would result in the highest possible discounted net timber revenue (DNR) while satisfying other management objectives unique to each series (limit on sediment, water allowed by drainage, and so on). The timber harvest and road construction activities in the FX and VR approaches and harvest activities in the MC approach were selected by the National Forest System personnel.

The discounted net revenues (DNR) per acre associated with the MX approach were significantly higher (95 percent confidence level) than the DNR values associated with the other three approaches. Average DNR per acre over the three areas was $402 for MX, compared to $269 for FX, $279 for VR, and $283 for MC. No statistically significant differences were found among the other approaches. In addition, the relative increase in efficiency associated with the MX approach (as measured by the percentage of the MX DNR obtained by other approaches within a series) was consistently larger the more complex the planning problem.

Differences in harvesting and road construction patterns were not consistent between the alternatives developed via the MX approach and the other approaches. In some instances, the difference in DNR was largely explained by the fact that the MX procedure selected harvest and road construction activities, which resulted in substantially lower discounted total transportation-related costs. In other instances the MX alternatives would harvest more timber and construct more miles of road, resulting in higher discounted costs, but also higher net revenues.

An additional harvest-volume-constrained MX alternative was developed for each test area to determine the effect on DNR of restricting the MX approach to the same harvest volumes by time period as the Series II VR and MC alternatives. DNR's per acre decreased relative to the Series II MX alternatives ($40 on the average) but were still significantly greater than the Series II VR and MC alternatives (differences averaged $86 and $82 per acre, respectively).

Data preparation over the three areas averaged 5.5 person-days per 1,000 acres having harvest potential in the next 50 years. An additional half person-day was required by the MX approach. There could be major differences in speed, efficiency, and error-checking among prospective computer programs for implementing any of the approaches. Once data are entered, the MX approach requires more computer resources due to the large number of calculations. The FX, VR, and possibly the MC approaches could be accomplished using a microcomputer or minicomputer.

Four Analytical Approaches for Integrating Land Management and Transportation Planning on Forest Lands

J. Greg Jones
James F. C. Hyde, III
Mary L. Meacham

INTRODUCTION

The Forest and Rangeland Renewable Resources Planning Act of 1974, the National Forest Management Act of 1976, and various implementing regulations mandate that forest management plans are developed for each National Forest. The purpose of this planning process is to develop the direction of management to be applied in the future. This includes selecting management prescriptions for each land delineation. In addition, forest planning also provides scheduling objectives for timber and other resource outputs, Forest-wide for the entire planning horizon and by management area for the first one or two decades. A management area is a grouping of acres having similar management objectives and a common management prescription. In some instances, it may be possible to disaggregate timber harvest schedules into smaller land delineations.

The need for analysis will not end with the forest planning process, however. Because of the magnitude of the task of developing a long-range, integrated plan for a National Forest (often 1 to 2 million acres in size), much of the analysis in forest planning has to be conducted at a relatively low resolution. As a result, while the type of management to be implemented is rather specific, the actual activities to carry out these management prescriptions are not specified in a site-specific manner. The challenge for the next level of analysis is to identify when and where treatment activities should occur in order to efficiently implement a plan.

Many resource managers believe that area-level analysis (ALA) is the logical next step once the information from a forest plan is extracted in as much detail as is practical and warranted. ALA is envisioned as an interdisciplinary process concerned with the management of geographically contiguous land areas from 5,000 to 50,000 acres in size. Specifically, it would concentrate on economic efficiency with regard to:

1. The location and timing of timber harvesting, road construction, and other land management activities.
2. Operational alternatives not previously specified in a forest plan, including analyzing such things as alternative silvicultural systems, logging systems, and road standards.
3. Cumulative environmental effects over time, including prediction of sedimentation and water yields in specific drainages or portions of drainages, the effect of harvesting and road construction on big game habitat, and so on.

The end result of ALA would be an operational plan for managing an area over, say, a 50-year period. Such a plan would identify the location and timing of timber harvest, road construction, and other management activities that are judged to be the most effective way to implement the forest plan in that area. This plan then provides specific direction for the projects to be conducted in an area.

The analytical approaches that could be used to conduct ALA range from "seat-of-the-pants" professional judgment, to computer-aided simulation approaches, to rather sophisticated optimization techniques. For most planning areas there would appear to be a large number of potential combinations of activities and timing sequences that could be used to implement forest plans. In addition, a number of pieces of information are necessary for developing and evaluating alternatives (timber volumes at various times, costs of various activities, sediment yields over time resulting from certain combinations of management activities, and so on).

Given the complexities of ALA, the advantages of some sort of computer-aided analysis seem apparent. The choice, it would seem, should be based on the following two questions. First, what differences in efficiency can be expected among the potential approaches? Second, what differences exist in terms of the resources required to conduct the potential approaches?

This report presents the results of a study that addressed these questions. The study tested four analytical approaches on three actual planning areas. These included two simulation approaches that vary by the flexibility allowed the user in selection of road access routes; a combination of simulation and optimization where the analyst makes harvesting and other land management choices and then uses an optimization procedure to minimize the road-related costs for accessing those activities; and an optimization procedure that selects both the land management activities and road

construction alternatives, based on a user-supplied objective function to be maximized or minimized, and user-supplied management constraints to be satisfied.

The paper is organized as follows. First, we discuss the basic formulation for ALA used in all four approaches (land and road network delineations, costs to be included, and so on). Then, we describe in more detail each of the four approaches. This section is followed by the study methods—experimental design, how each approach was applied, and so on. Finally, we present the results of the comparisons and our conclusions.

DEVELOPING A BASIC FORMULATION FOR ALA

Delineating Land Area

Each area was delineated into potential harvesting units, based on logging, site preparation, and regeneration considerations. Figure 1 illustrates the units established for the Twin Rocks area, one of the three test areas in the study.

Many strategies were available for delineating land, for example, categorizing by vegetation, site productivity, or topographical features. The potential harvesting unit strategy was selected because it provides the spatial orientation needed for ALA. This approach ensures that members of an interdisciplinary team have the same image of proposed alternatives. This cannot be accomplished when harvest alternatives are formulated in terms of percentages of land categories to be harvested. In addition, harvest alternatives need to be geographically specific if transportation strategies are to be analyzed in sufficient detail.

Timber Management Projects

Timber management projects that implement the management objectives specified in the forest plan were developed for each of the potential harvesting units. A given project includes a schedule of activities (such as sale preparation, timber harvest, site preparation, and regeneration) to be applied on a potential harvesting unit. Alternative timings for activities were handled by developing alternative projects with different timings. In some instances a forest plan prescription may allow for operational alternatives, such as silvicultural system or logging method. These alternatives are included by developing timber management projects for each option.

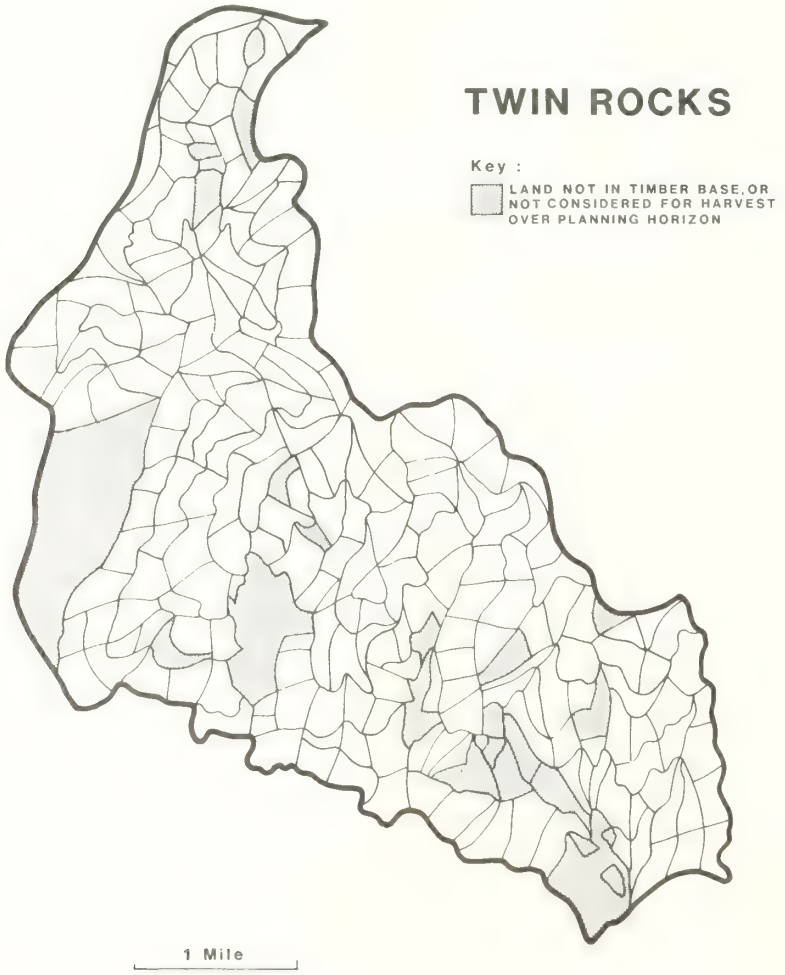


Figure 1.—Potential harvest units for Twin Rocks.

Potential Transportation Network

The transportation portion of ALA is based on a potential transportation network. This network must be compatible with the potential harvesting units and logging methods, as well as the expected kinds and amounts of traffic. At this point, a reasonable number of routes should be included to provide alternative access routes to potential harvest units and groups of units.

Once developed, a potential network is delineated into "links," which are bounded by "nodes." This concept is illustrated in figure 2, which presents the network for the Twin Rocks test area.

Road Construction Projects

Road construction (or reconstruction) projects were developed for the links representing proposed roads or existing roads requiring reconstruction. The projects for a given link vary primarily by the timing of the construction or reconstruction. In addition, road standard alternatives were included for a link when it was not clear prior to an analysis what standard is most appropriate. When a potential road network includes more access routes than necessary (to provide alternative transportation strategies), some of the links would not be selected for construction in a given alternative.

Analysis Approaches Tested

The study tested four computerized analytical approaches for use in ALA. These were: (1) fixed-access simulation (FX), (2) variable-access simulation (VR), (3) simulation with minimization of transportation-related cost (MC), and (4) optimization (MX). It is appropriate to think of these approaches as "generic" categories. That is, we were testing approaches, **not** computer software. Several software systems exist that could accomplish parts or all of several of these approaches, and any number of new systems could be developed.

Each of the four approaches is based on the formulation just described. Therefore, the first step in each approach is to develop the potential harvest units, the timber management projects, the potential transportation network, and the links and road construction projects.

Fixed-Access Simulation (FX).—In the FX approach, the analyst must choose among the timber management projects and road construction projects. A computer simulation program is used only to aid in calculating useful information for evaluating area plans. This approach represents a rather simplistic simulation design. After development of the potential harvest units, road links, and associated management and construction options, the analyst identifies the road links that access

Figure 2.—Potential road network for Twin Rocks.

each potential harvest unit. This transportation strategy is then locked in (**fixed**) for the remainder of an analysis.

Next, the analyst chooses among the timber management projects developed for the potential harvest units. These selections are entered into the program, which determines (from the fixed transportation strategy developed earlier) the links to be constructed by time period and road standard to access the units selected for treatment. The program then calculates information for evaluating the management alternative entered for the area. This includes such things as discounted net timber revenue, net timber revenue by time period, costs by several categories, sediment by drainage and time period, and so on. The analyst then studies the results, makes desired modifications in the selection of land management projects, and runs the simulation program again. It may take numerous "runs" to develop an alternative for an area that is judged to be desirable.

Variable-Access Simulation (VR).—The VR approach is more sophisticated than the FX approach in that the analyst is given the opportunity to modify the choice of road links that access potential harvest units between simulation runs.

This approach also begins with an analyst-specified transportation strategy. Here, however, it is only tentative and used primarily for calculating information that aids in the selection of resource and road construction projects (timber revenue net of haul and other costs, construction costs, sediment per project, and so on). The analyst then makes the initial selections of resource and road projects and enters them into the computer. Road projects could be entered as a list, or as modifications from the tentative transportation strategy entered earlier. The program then calculates the results of the selections as in the FX approach (discounted net timber revenue, costs, sediment by drainage, and time period, and so on). The analyst then makes any desired modifications, including changes in either resource or road projects, and runs the simulation program again. This process is repeated until a satisfactory alternative is developed. The simulation program PASS (USDA Forest Service 1985) fits into the variable-access simulation category.

Simulation with Minimization of Road Cost (MC).—The MC approach combines a simulation approach for land management activities with a cost minimization routine for selecting road construction projects. The resource projects are selected by the analyst and entered into a computer system, as in the first two approaches. Such a system, however, then utilizes a network optimization routine to select the combination of road construction projects that provides access for the selected land management activities at the least overall transportation-related cost. This cost is defined as the sum of haul, maintenance, road construction, and reconstruction costs expressed in present value (discounted) terms. Once the selection of road projects has been made, the computer program calculates the same type of information for evaluating the alternatives as the simulation approaches (discounted net timber revenue, costs, sediment by drainage, and time period). The analyst has the option of modifying the selection of resource projects and repeating the process.

Several examples of cost-minimizing network models that might be used in the MC approach include: MINCOST (Schnelle 1977), the Timber Transport Model (Sullivan and Barnes 1980), TRANSHIP (Kirby and others 1981a), and NET4T (Sessions 1985).

Optimization (MX).—In the MX approach, a computerized optimization model selects the combination of timber management projects and road construction projects that maximize or minimize some objective and satisfy specified management constraints. The analyst must specify an objective function to be maximized (or minimized). We envision that maximizing discounted net revenue (DNR) would be frequently used in ALA, although other objective functions could be used as well; for example, minimizing discounted total cost, maximizing timber volume, or minimizing quantity of sediment. In addition, the analyst has the option of including management objectives that cannot easily be reflected in an objective function as constraints to be satisfied. This could include such things as sediment or water yield for which it is difficult (or impossible) to estimate dollar values.

Once the objective function and constraints have been specified, the solution is found that identifies the combination of resource and road construction projects that maximizes (or minimizes) the specified objective function while satisfying the constraints. In addition, the model calculates (based on the selection of resource and road projects) the same type of information for evaluating the alternatives as the first three approaches. The analyst then has the option of modifying the constraints or selecting a different objective function and reoptimizing the model.

The Integrated Resource Planning Model (IRPM) (Kirby and others 1981b) and a test release of FORPLAN Version II (Johnson 1985) are two examples of existing computer systems that could potentially be used to conduct this type of optimization analysis.

TESTING ANALYTICAL APPROACHES

Test Areas

The four analytical approaches were tested on three areas. The objective in selecting the three test areas was to provide a range of conditions over which to compare the four approaches. One area was to be small in size, with a planning problem of no more than moderate complexity; a second area was to be of moderate size and complexity; and the third area, large, with a relatively complex planning problem. It was hypothesized that complexity in planning is affected by such factors as the distribution of merchantable timber coupled with topography; environmental, and other nontimber objectives; and the shape of the proposed transportation network. In reality, the choice of test areas was limited by the number of Forest Service District offices that expressed interest in cooperating in the study and by the areas offered for analysis.

The three test areas chosen (location shown in fig. 3) are described below:

Twin Rocks Area (fig. 1)

—Lolo National Forest

—6,400 acres (total)

—5,950 acres with harvest alternatives in the 50-year planning horizon

—About 10 percent of area is currently accessible by existing roads not requiring reconstruction.

—Virtually no harvesting has been done in area in the past.

—The road network is best described as a "grid" network in that there are a number of potential connecting roads (fig. 2).

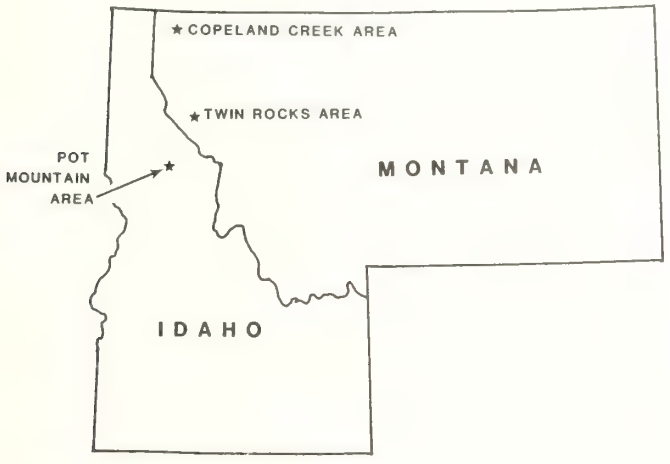


Figure 3.—Location of test areas.

Copeland Creek Area (fig. 4)

—Kootenai National Forest

—16,870 acres (total)

—8,640 acres with harvest alternatives in the 50-year planning horizon

—About 40 percent of area is currently accessible by existing roads requiring no reconstruction.

—There are a number of harvest units from previous sales in early stages of regeneration in area.

—The road network is best described as two trees placed top-to-top with a few connecting branches (fig. 5).

Figure 4.—Potential harvest units for Copeland Creek.

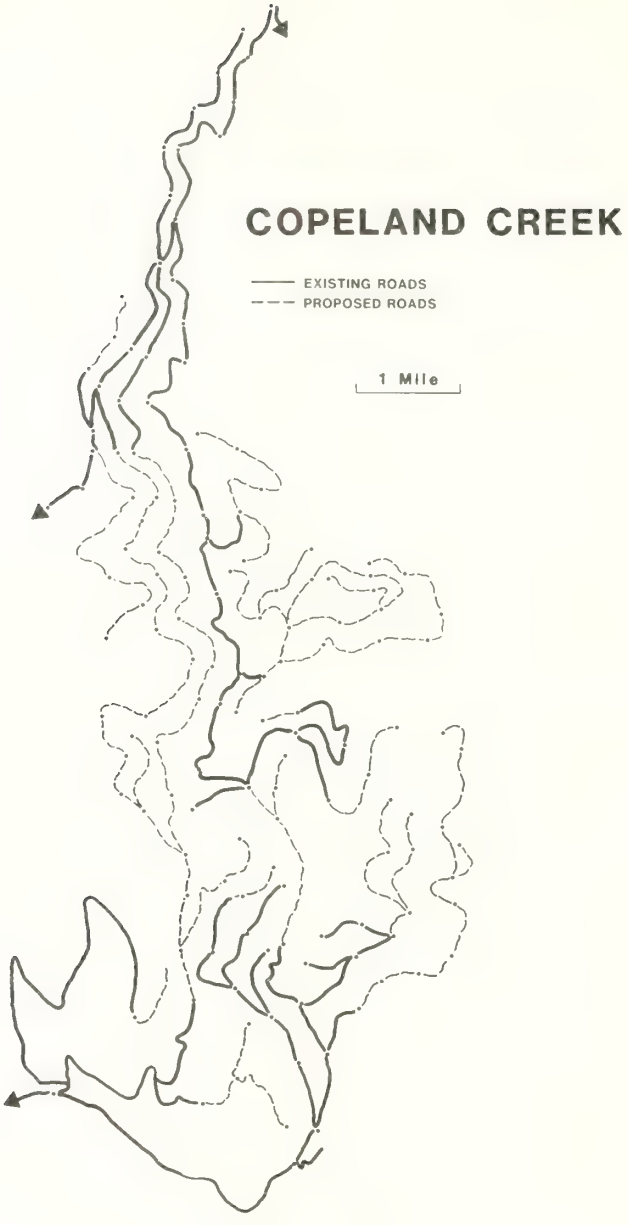


Figure 5.—Potential road network for Copeland Creek.

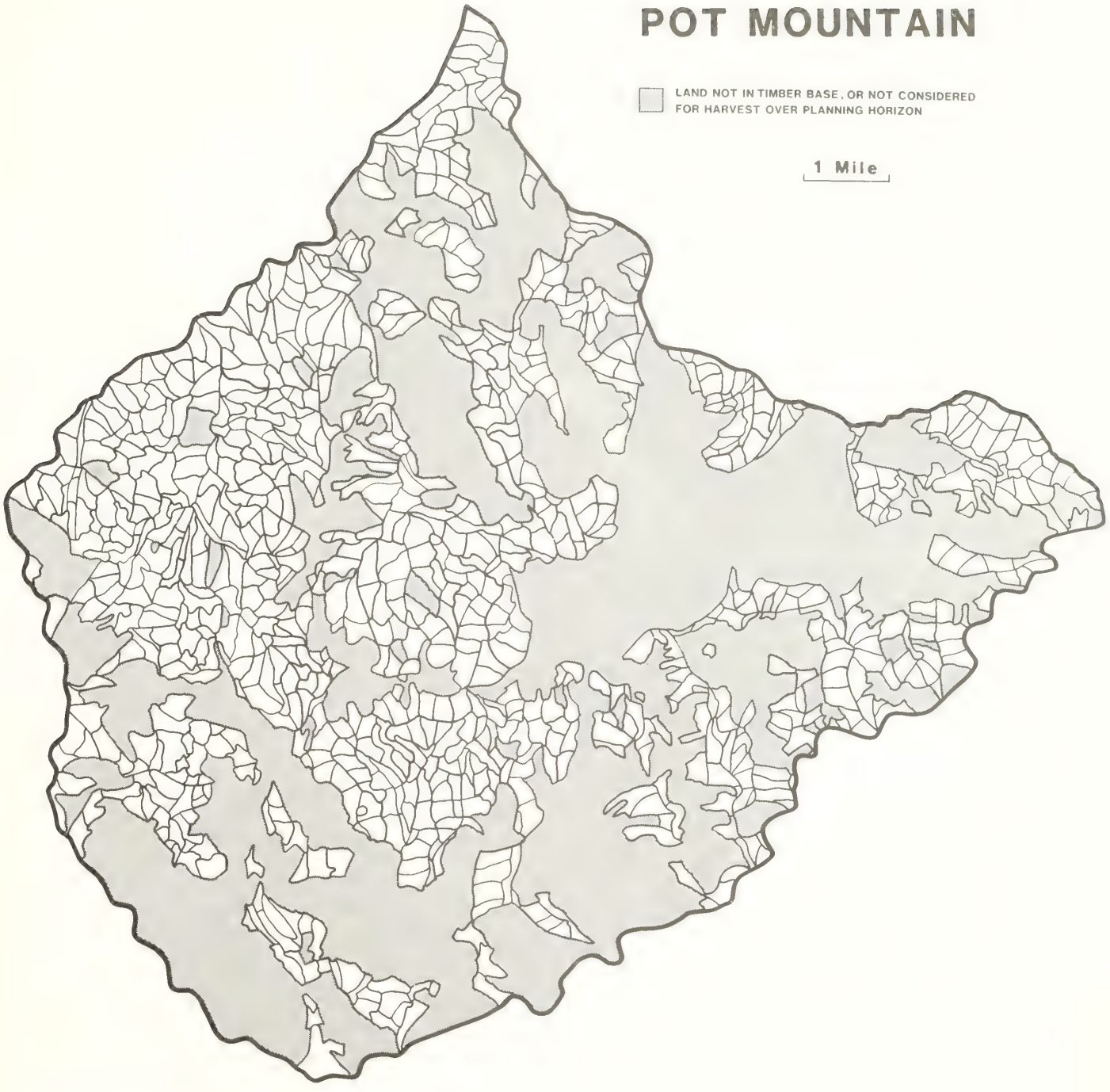


Figure 6.—Potential harvest units for Pot Mountain.

Pot Mountain Area (fig. 6)

—Clearwater National Forest

—51,870 acres (total)

—25,950 acres with harvest alternatives in the 50-year planning horizon

—About 5 percent of area is currently accessible by existing roads not requiring reconstruction.

—Essentially no harvesting has occurred in the area in the past.

—The road network has a main loop through the area, a smaller loop off the main loop, and a number of smaller tree-shaped networks feeding into these loops (fig.7).

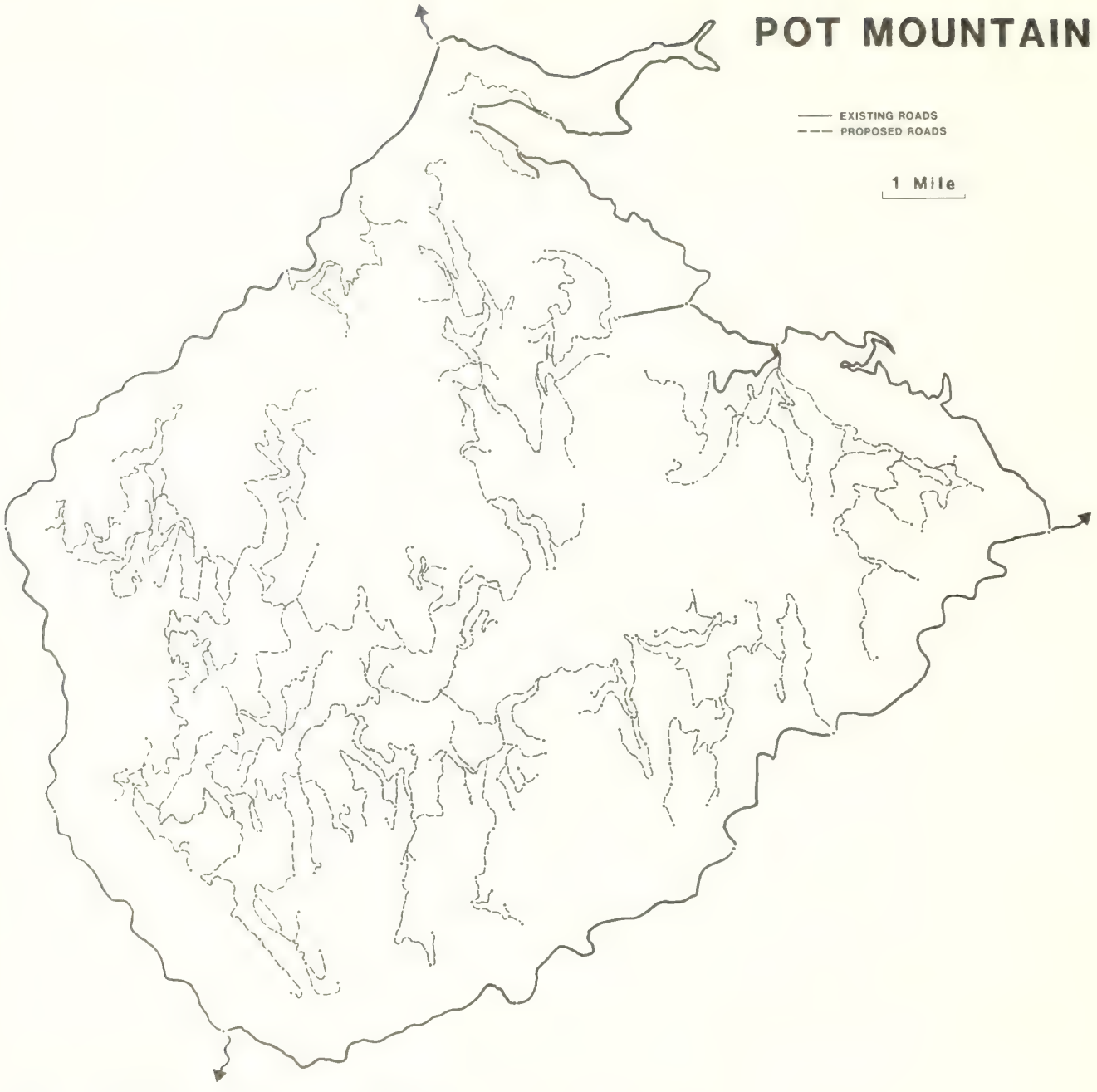


Figure 7.—Potential road network for Pot Mountain.

Summary of Data Used

Data for the test areas were furnished by the cooperating District and Forest personnel. In addition, whenever professional or managerial judgments were required (such as location of roads and potential harvesting units), those judgments were made by National Forest System personnel. The following discussion summarizes the various categories of data used.

Potential Harvest Unit Delineations and Resource Projects.—The land within each test area was delineated into potential harvest units, as described earlier under Developing the Basic Formulation for ALA. The criteria used for delineation were that the units be consistent with the type of management identified for the area and that the units represent what appears to be an efficient design with regard to logging method and road location. Units varied in size, with the largest being about 40 acres.

Timber management projects, which identified packages of land management and timber harvest activities, were developed for each potential cutting unit. Each project included all the activities that occur from sale preparation to regeneration of the site. Composition of the projects followed the type of management to be applied, as identified in forest planning. Therefore, the projects for a given unit differed primarily by the timing

of activities. Choice of silvicultural system was also an option for about a third of the cutting units whenever more than one approach to cutting unit management was possible and yet consistent with the forest plan. Finally, there was a choice between skyline and helicopter logging systems for a few units.

Transportation Network and Road Construction Projects.—Potential transportation networks were developed for each area (figs. 2, 5, and 7). These networks are operationally viable (potential roads can be built within a horizontal tolerance of about ±100 feet) and compatible with the type of management and logging systems identified for the area. The networks were delineated into links in a manner that provided a reasonable amount of analytical detail (the amount links overshoot or undershoot access to units was kept to a minimal level) yet held the number of links to an amount which can be handled efficiently in an analysis.

Construction projects were then developed for the links representing proposed new roads and for links representing existing roads that require some reconstruction. The road alternatives developed for each link varied by the time period in which construction would occur and, for some links, by road standard. The road project costs included road design and layout as well as the construction itself.

Time Periods.—This study adopted a 50-year planning horizon composed of the following time periods:

Time period	Decades
1	1
2	2
3	3-5

This choice of time periods resulted from a compromise of three objectives: (1) the first two time periods should sum to no more than 20 years so that a fair amount of time specificity can be maintained in the early portion of the planning horizon, (2) the time periods should provide ability to analyze trade-offs between conducting specific activities in the near future versus the more distant future, and (3) the number of time periods should be held to a minimum to keep the analysis as simple as possible.

Yield Information.—Five types of physical yield information were included for the three test areas, although only timber yields were present in each of the three areas. Timber yields for each potential harvesting unit were projected to the midpoints of each time period. Because the potential harvesting units were site-specific, yield projections were based on the most specific timber data available.

Two of the yield categories measured big game forage production: thousands of pounds, dry weight and acreage in forage-production. The latter was used in calculating cover/forage ratios and for constraining these ratios between specified lower and upper limits. Both measures of big game forage production were tied to the type of harvest. Predicted increases in forage production due to harvesting (which typically peaks within 20 to 30 years after harvest and then decreases as trees become reestablished) were projected from the time of disturbance through the planning horizon. Both were measured in terms of annual average quantity per decade.

The remaining two yield categories, water and sediment yields, were included to assess environmental impacts. Water yields were tied to timber harvest activities and sediment to road construction and harvest activities. Water and sediment increases (which generally peak within 10 years after disturbance and then decrease as the disturbed area becomes revegetated) were projected from time of disturbance through the planning horizon. Both were measured as an annual average quantity per decade.

Economic Information.—Timber was the only output valued in dollars. The basis for timber prices was mill-delivered logs. Species categories were used to handle variations in unit value. Costs included all purchaser costs for harvesting, haul and road maintenance, and contract-related costs such as slash disposal. Forest Service costs included road construction (regardless of method of financing), road design and layout, brush disposal and regeneration of timber, sale preparation and administration, and postsale silvicultural exams. Agency costs that do not vary as a result of these activities (Regional Office and Washington Office overhead costs) were not included.

All timber prices and costs were expressed in 1982 dollars. Assumptions about real changes in prices and costs were the same as those used in the respective forest planning processes. A real dollar discount rate of 4 percent was used.

There were several reasons for valuing timber as delivered logs and including purchaser costs (rather than using stumpage prices). Forest Service design of road networks and timber sales can affect purchaser costs, which in turn are counted against the price of stumpage. Road network design affects haul costs and road construction costs. Timber sale design affects stump-to-truck costs, purchaser slash disposal costs, and other costs associated with specifications in timber sale contracts. Any cost the Forest Service imposes on a purchaser can be expected, on the average, to be subtracted from the amount the Forest Service receives for the timber sold. Thus purchaser costs can be expected to have the same effect on DNR for the Forest Service as costs incurred directly by the Forest Service.

Valuing timber as delivered logs and subtracting both purchaser costs and Forest Service costs has two advantages over the alternative of valuing the timber—such as would be done using a transactions evidence approach based on stumpage price. First, haul cost can be handled explicitly in the transportation analysis conducted in ALA. In some instances there are trade-offs to be made between higher haul costs and lower road construction costs and vice versa. In contrast, haul cost is implied (imbedded) in stumpage price. Therefore, the only transportation analysis that can be accomplished in ALA when stumpage price is used directly to value timber involves minimizing road construction cost. Any trade-offs between haul cost and construction cost cannot be addressed. Second, valuing timber as delivered logs allows for explicitly identifying and treating other cost components (for example, stump-to-truck costs, purchaser slash disposal costs) that are "hidden" in stumpage price values.

Comparing Approaches

Each approach was applied twice (Series I and Series II) on each area. The objective for Series I was to develop an area plan with discounted net revenue (DNR) as large as possible, while satisfying the adjacency rule. This rule states that, if a unit is harvested, an adjacent unit cannot be harvested for at least two decades. This is roughly the amount of time it takes to regenerate and grow the new stand of trees to a size such that the unit again appears forested and no longer is considered an "opening." This rule, along with the size limitations on the potential harvest units themselves, maintains harvest openings to a size consistent with Forest Service policy. The intent of Series I was to develop a baseline alternative that shows the largest net timber revenue that could be obtained over the planning horizon, with only very minimal environmental restrictions.

For Series II, the objective was to develop a plan with DNR as large as possible while achieving environmental objectives and meeting the adjacency rule (see table 1). The Series II plans represent packages of activities that are consistent with the management approach selected in the forest planning process.

Additional series could also have been developed with somewhat different objectives, yet consistent with forest plan direction. For example, a Series III might have included a harvest volume objective. Time and budget considerations did not permit the development of additional series.

DNR is a measure of the net effect area management has on the overall financial receipts experienced by the Forest Service, expressed in discounted dollars. It contains the following value and cost components:

Start: $ Log value (mill-delivered)
(+) Bid premium
(−) Haul and maintenance costs
(−) Purchaser slash disposal costs
(−) Logging costs
(−) Profit and risk margin
= $ Stumpage price (≅ "high bid")
(−) Road costs or purchaser road credits
(−) Site improvement, regeneration, and brush disposal costs
= $ Indicated net stumpage value
(−) Sale preparation cost (including specialists)
(−) Sale administration cost
(−) Silvicultural examination cost
End: = $ Net revenue for Forest Service

DNR was chosen as the objective that each of the approaches would attempt to maximize because it provides a good measure of long-run timber management efficiency. Any alternative that maximizes DNR and simultaneously satisfies other resource objectives is efficient. Any number of efficient plans could be developed, each with a somewhat different mix of outputs. It is the responsibility of the resource manager to evaluate which plan is preferred. In this study, DNR comparisons reflect the effectiveness of each analytical approach in developing efficient management plans.

One could alternatively attempt to maximize (or minimize) other objectives (for example, minimize overall cost or maximize timber volume). It is believed, however, that using other objectives would not affect the comparisons among the analytical approaches. That is, the approach that gives rise to the highest DNR would also give rise to the highest value regardless of the objective to be maximized, or to the lowest value for any objective to be minimized.

Modeling Procedures

An optimization model was built for each area using the Integrated Resource Planning Model (IRPM) (Kirby and others 1981b) available at the USDA Fort Collins Computer Center. These models were used for each of the four analytical approaches. For the simulation approaches, the harvesting and road construction alternatives selected for implementation were forced into solution via equality constraints. Thus, for these approaches the optimization models were run as if they were simulation models, because no choice remained regarding selection of harvest or road construction projects.

Using the same model for all four approaches ensured that exactly the same information (costs, prices, yields) was used in each. Second, it alleviated the need for developing necessary software for conducting the simulation approaches.

Description of IRPM Models.—IRPM is a mathematical modeling system in the general class of analysis known as mixed-integer linear programming. Three categories of variables are used in these models: (1) timber management projects, (2) road construction projects, and (3) traffic variables.

The timber management projects represent the harvesting alternatives for the potential harvest units. As described earlier, a timber management project includes all the on-site activities associated with harvesting and regenerating a potential harvest unit. The only costs not included in the coefficients for these projects are the haul and maintenance costs and road construction and reconstruction costs. The timber management projects were allowed to assume any value between 0 (don't do project) and 1.0 (do project in its entirety). Fractional values measure the portion of a project selected for implementation. In actuality, the majority of projects selected (above 80 percent in most cases) were entire projects.

The road construction projects represent the construction and reconstruction alternatives for the links in the road networks. Road projects were limited to values of 0 (don't do project) and 1.0 (do project). If fractional values were to be permitted, the transportation network would be discontinuous, which would be nonsensical. Road construction projects contribute road construction cost to the DNR calculations.

The third type of variables, traffic variables, was formulated as ordinary continuous variables (which can assume any nonnegative value). They measure the quantity of traffic flowing over each link by time period and road standard. Traffic variables contribute haul and maintenance cost to the DNR calculations.

The other main component of IRPM models is the constraints, which fall into two categories. The first category is the constraints that are required for the model to operate properly. These include: (1) constraints that limit to one the number of resource projects that can be simultaneously allocated on a cutting unit, (2) constraints on road project variables that ensure access for resource projects, (3) constraints that "connect" the traffic variables so they correctly measure the volume of traffic flowing over the road segments, and (4) various other constraints of similar nature. For the most part, these constraints are developed by IRPM software and will not be discussed further here.

The second category of constraints is the user-specified constraint rows. These include the management objectives listed in table 1 (which were entered as constraints), plus assorted other rows for monitoring cost categories, volume harvested by species categories, and so on. In linear programming, the user has the option of defining rows as either constraining or nonconstraining. With the exception of the constraints listed in table 1, the rows in this second category were treated as nonconstraining rows.

Fixed-Access Simulation (FX).—The first step following the development of units, resource projects, and road projects was for the cooperating National Forest System (NFS) personnel to develop the transportation plan that identified which links would be constructed to access each unit. The three transportation plans were based on analyses done using the MINCOST model (Schnelle 1977). Figure 8 presents the fixed access transportation plan developed for the Twin Rocks area.

Based on these transportation plans, the following information was calculated and supplied to the cooperating NFS personnel:

—List of discounted net revenues per acre net of haul cost for each timber management project.
—List of discounted construction costs by time period for each road link.

Given this information, the cooperating NFS personnel chose the combination of harvesting activities (resource projects) they thought would give the greatest DNR while satisfying the other objectives established for Series I and II. These selections were entered into the computer model along with the required road construction projects predetermined from the transportation plan. The model was then used to calculate total DNR, costs, sediment, and so on. The results were provided to the NFS personnel who made whatever modifications appeared necessary to either improve DNR for the area or satisfy the Series I or II objectives. The revised alternative was again run through the computer model and the results returned to the NFS personnel. This process was continued until the cooperators believed they had identified that combination of activities that would provide the highest DNR while satisfying the other objectives. The number of runs made to develop an alternative varied from one to nine.

Variable-Access Simulation (VR).—The process used for the variable-access approach was essentially the same as that described for the fixed-access approach. This approach, however, permitted the NFS personnel to change the route by which the units were to be accessed as well as which units were to be harvested. The number of runs made to develop alternatives via this approach varied from two to nine.

Simulation with Minimization of Road Cost (MC).—The final harvesting alternatives selected in the variable-access simulation were used in this approach. These selections were specified ("hardwired") in the optimization model, which was then used to minimize discounted total transportation cost. In essence, the IRPM models were operated as if they were TRANSHIP models minimizing network costs (Kirby and others 1981a). In addition to selecting the road construction and reconstruction projects for accessing the specified timber management activities, the solution process calculated DNR, costs, sediment, and so on, based on the specified timber projects and selected road projects.

Table 1.—Management objectives (constraints) used in applying each of the four analytical approaches by series and test area

Test area	Series I	Series II			
	Adjacency	Adjacency	Water[1]	Sediment[1]	Cover/forage[2]
Twin Rocks	Adjacent units could not be harvested within TP1 and TP2, or within TP3	Same as Series I	Initial increase ≤8%	Not used	Not used
Copeland Creek	Adjacent units could not be harvested within TP1 and TP2, or within TP3	Same as Series I	Average annual increase ≤20%	Average annual increase ≤80%	Not used
Pot Mountain	Adjacent units could not be harvested within TP1 and TP2, or within TP3	Same as Series I	Not used	Average annual increase ≤48%	Cover, summer range ≥43% Cover, winter range ≥23%

[1]Applied separately by drainage.
[2]Applied separately by wildlife management area.

Figure 8.—Fixed-access transportation plan for Twin Rocks.

The TRANSHIP formulation (and IRPM) require solutions in which the road construction projects assume values of 0 or 1.0 (recall fractional values would give rise to a meaningless discontinuous transportation system). One option for attaining such solutions is using a mixed-integer programming (MIP) algorithm. This is feasible, though, with only very small models, say, less than 50 to 100 integer variables. The size of the models to be optimized in this study (smallest contained about 2,000 rows and columns and about 400 integer variables) made using MIP algorithms cost-prohibitive. Instead, a heuristic procedure, which takes advantage of the type of MIP problem developed by IRPM, was used to attain MIP solutions. The heuristic procedure does not produce truly optimal MIP solutions, but is thought to provide good solutions for these formulations. (See USDA Forest Service 1983 for a more complete description of the heuristic procedure.)

Optimization (MX).—For this approach, the optimization model was run as it was designed to operate. The objective function maximized was DNR. The heuristic process used to attain MIP solutions in the MC approach was also used for the MX solutions. The adjacency rule and Series II objectives listed in table 1 were included as constraints. The solution process simultaneously selected timber management activities and road projects (subject to the constraints) while calculating the resulting costs, sediment, and other factors.

RESULTS AND DISCUSSION

An area plan developed by one of the four approaches is shown in figure 9. In this alternative for the Twin Rocks area about three-fourths of the units are scheduled for harvest in the three time periods. Proposed road links scheduled for construction and existing roads scheduled for reconstruction are identified by the time periods (written next to the links) which signify proposed timing for construction. Only a portion of the network presented earlier (fig. 2) is proposed for construction in the 50-year planning horizon.

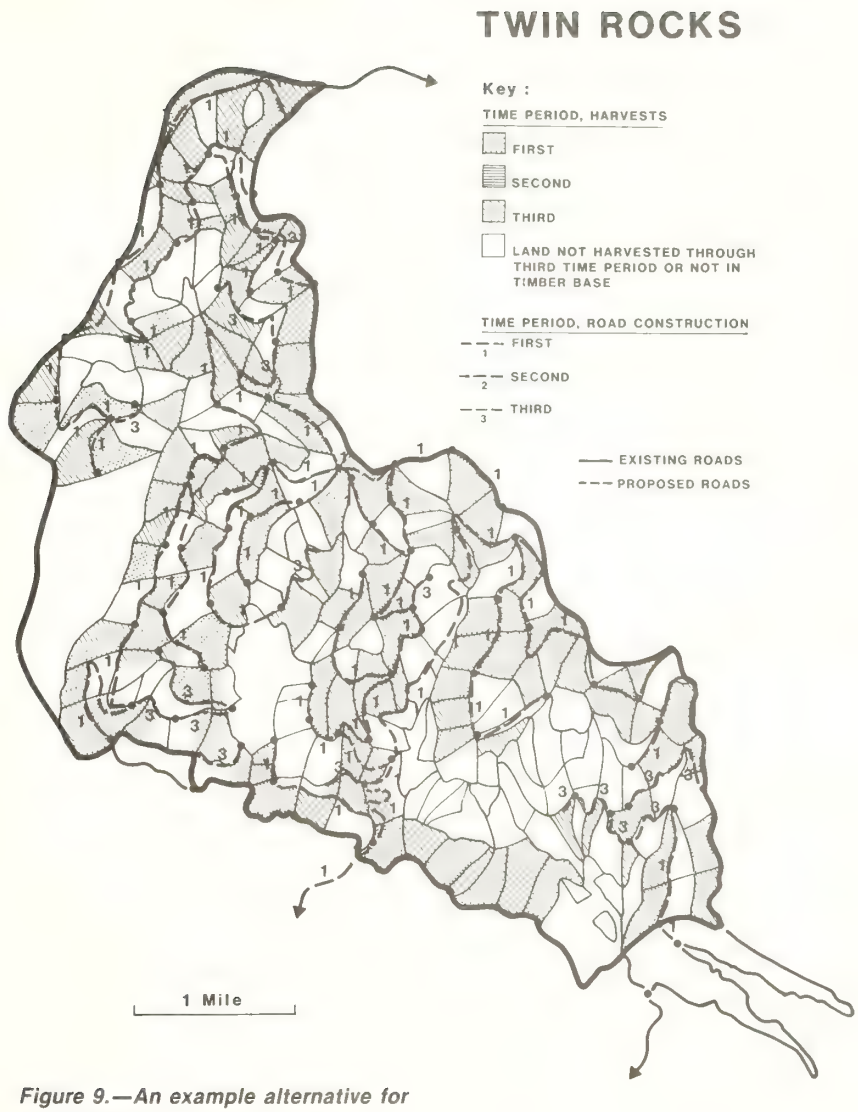


Figure 9.—An example alternative for Twin Rocks.

Plotting results as shown in figure 9 provide analysts and managers with a geographic representation of an alternative. But such plots provide little information for comparing approaches. For this purpose it is more meaningful to look at various statistics calculated from plans developed by the approaches: DNR, miles of road to be constructed, volume of timber to be harvested, and so on.

DNR Comparisons

The DNR's developed via each approach are presented in figure 10. Here, DNR is presented on a per-acre basis (total DNR divided by the total number of acres for which there are potential harvesting activities) to facilitate comparisons across the test areas, which varied greatly in size. The percentages at the top of the bar graphs express DNR for each approach as a percentage of the DNR for the MX approach.

The most striking aspect of figure 10 is the amount by which DNR for the MX approach exceeds those for the other approaches. For the Twin Rocks area the MX approach has a DNR that is $70 per acre greater than the MC approach (highest DNR of the first three approaches) in Series I, and $91 more in Series II. For the Copeland Creek and Pot Mountain areas, the dollar differences between the MX and other approaches are larger. The difference in DNR per acre between MC and MX is $141 for Copeland Creek Series II, and $134 for Pot Mountain Series II. Yet the percentage differences in DNR between each of the first three approaches (FX, VR, and MC) and the MX approach were smaller for Copeland Creek and Pot Mountain than for Twin Rocks.

Differences within the first three approaches were smaller. In fact, there were essentially no differences in the DNR's per acre calculated for the FX, VR, and MC approaches on either Copeland Creek or Pot Mountain. On the Twin Rocks area, DNR for the VR approach exceeded the FX approach by $24 per acre in both Series I and II. The increase between MC and VR was less at $8 per acre for Series I and $6 per acre for Series II.

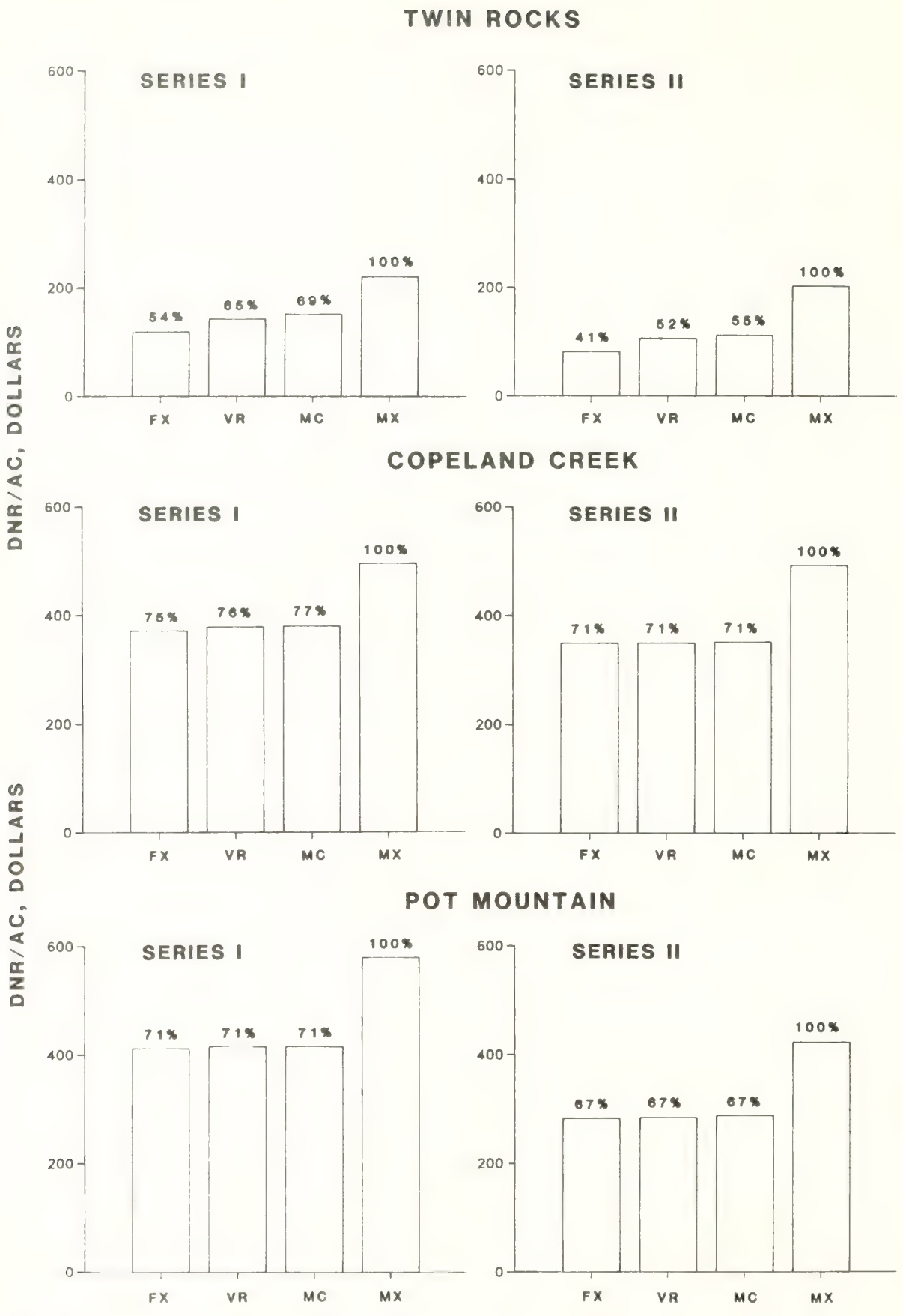


Figure 10.—Average DNR per acre from each approach by series and test area.

A two-way analysis of variance was performed to test for significance in the differences in DNR (fig. 11). It was hypothesized that the analysis technique and test area both influence DNR. The F-values indicate that there are statistically significant differences (95 percent confidence level) in DNR among the approaches and the test areas themselves. The confidence intervals for the DNR means presented in figure 11 indicate where those differences are located. The DNR's calculated for the MX approach are significantly higher than the DNR's associated with the other three approaches (significant differences are indicated when the confidence intervals do not overlap). There are, however, no significant differences indicated among the FX, VR, and MC approaches. Finally, the DNR's associated with the Twin Rocks area are significantly lower than the other two test areas.

The results presented in figure 10 indicate that the MX approach can be expected to provide area plans with significantly higher DNR's than the other approaches. Next, it was hypothesized that these differences are greater the more complex the planning problem. This hypothesis was tested by performing an analysis of variance on the percentage of the MX DNR achieved by the FX, VR, and MC approaches. Complexity was measured in two ways. First, the Series II planning problems are more complex than the Series I problems because they include sediment, water, and cover/forage objectives as well as the adjacency rule present in both series. Second, complexity varied across test areas. The Twin Rocks area had a more complex transportation aspect due to its grid-shaped network.

ANALYSIS OF VARIANCE

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F-Statistics
Area	2	331,925	165,962	48.8*
Approach	3	70,636	23,545	6.9*
Interaction	6	3,188	531	.2
Error	12	40,778	3,398	
Total	23	446,527		

*Statistically significant at the 95 percent confidence level

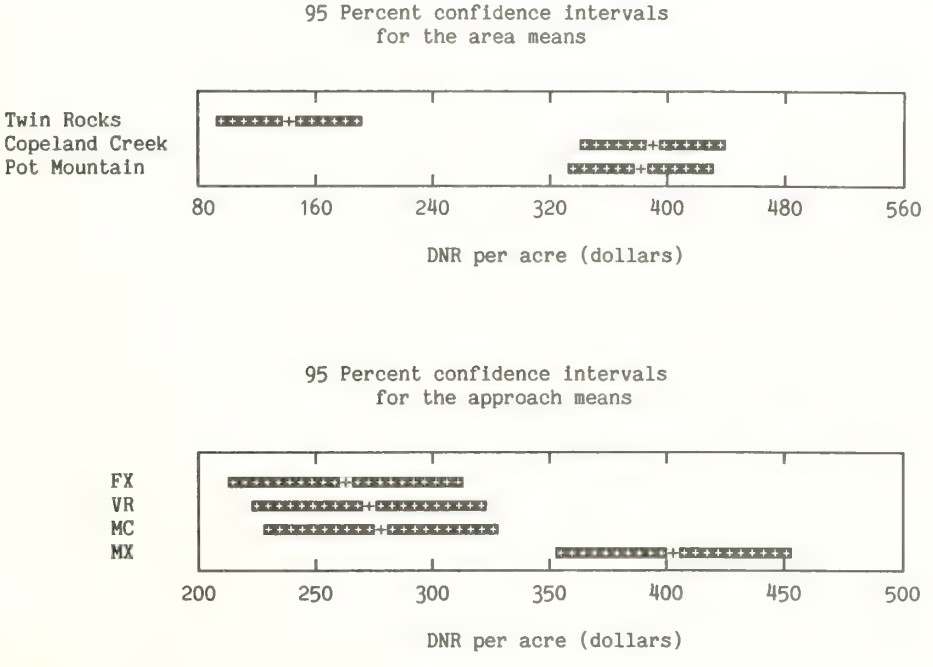


Figure 11.—Statistical test for differences in average DNR per acre across area and approach.

The results of this analysis of variance are presented in figure 12. The F-values for both area and series indicate significant differences at the 95 percent confidence level. The confidence intervals around the area means indicate that the percentage of the MX DNR achieved by the other three approaches was significantly lower for the more complex Twin Rocks area than the other areas. Second, the confidence intervals around the series means indicate that the percentage of the MX DNR achieved by the other three approaches is less for the more complex Series II planning problems. These results support the hypothesis that the more complex the planning problem the greater the differences in DNR between the MX approach and the other three approaches.

Differences in Other Factors

Amounts predicted for other factors help explain the differences observed in DNR and are also of interest in their own right. These factors will be discussed for each test area.

Twin Rocks Area.—Figure 13 presents a number of items for the Series I alternatives. First, consider the alternatives developed by the FX, VR, and MC approaches. The harvest quantities are the same for each of these alternatives. In fact, the same units were selected for harvest in each. Therefore, the differences in transportation-related costs account for the entire differences in DNR across these alternatives. Miles of new road to be constructed in time period 1 decrease as one

ANALYSIS OF VARIANCE

Source	Degrees of Freedom	Sums of Squares	Mean Squares	F-Statistics
Area	2	1,010.5	505.3	26.0*
Series	1	252.4	252.4	13.0*
Interaction	2	83.1	41.5	2.1
Error	12	232.5	19.4	
Total	17	1,578.5		

*Statistically significant at the 95 percent confidence level

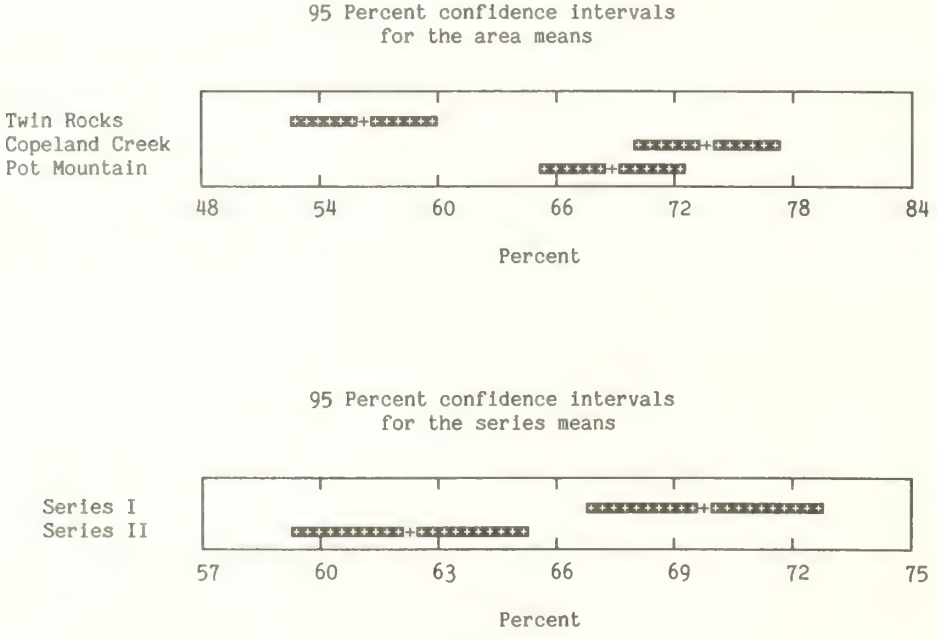


Figure 12.—Statistical test for differences in the percentage of the MX alternatives achieved by the FX, VR, and MC alternatives across area and series.

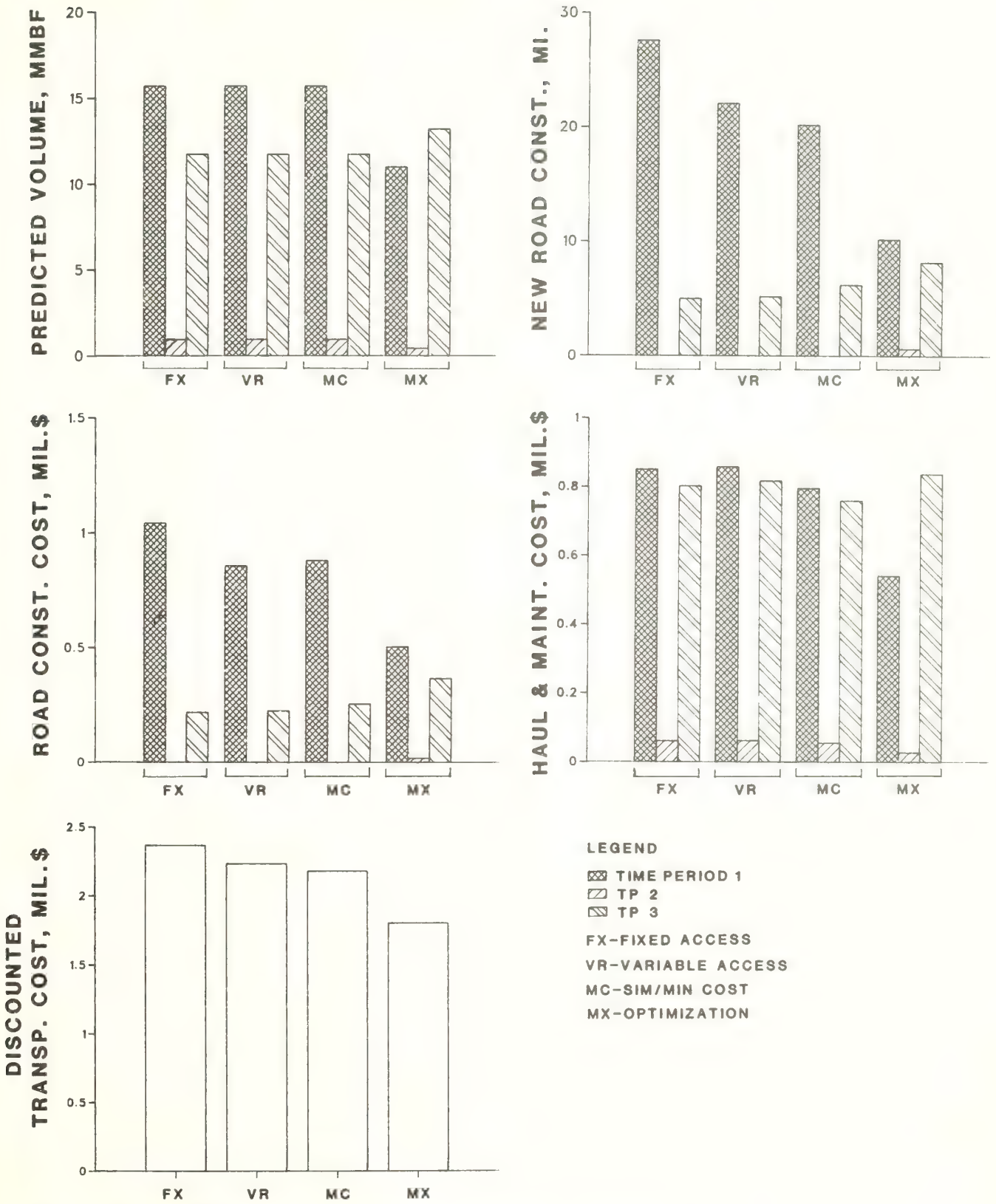


Figure 13.—Items of interest for the Twin Rocks Series I alternatives. (Time period 3 is presented on an averaged decade basis.)

goes from the FX to the VR to the MC alternative. But the reduction in number of miles of new road construction is not the entire story. In time period 1, road construction cost is less for VR than for FX, but the VR haul cost is higher. The net result is a lower total transportation cost in time period 1 for VR. In time period 3, both road construction cost and haul cost are higher for VR. The net result is a discounted total cost for VR that is about $131,000 less than FX.

In the VR and MC approaches trade-offs in haul and construction costs were also made between time periods. Even though fewer miles of road would be constructed in time period 1, construction cost is $25,000 higher for the MC alternative. This increase is offset by lower haul costs, resulting in a total transportation cost for the MC alternative that is $37,000 less in time period 1. The same pattern of higher construction costs but lower haul costs for the MC alternative also occurred in time period 3. The net result was a discounted total cost for MC that is about $57,000 less than the discounted cost for VR.

An important difference between the MX alternative and the other approaches is the quantity of timber to be harvested. The MX alternative would harvest about 5 million bd ft less in time period 1 and about 2 million bd ft per decade more in time period 3. Also, different units were selected for harvest.

There were major differences in the transportation aspect of the Series I MX alternative as well. It would construct substantially fewer miles of road in time period 1, with an accompanying lower overall transportation cost. Then, in the third time period it would construct more miles of road, incurring a higher construction cost.

Much of the difference in DNR between the Series I MX alternative and the other approaches is due to its lower overall discounted total transportation costs. Comparing the MX and MC alternatives illustrates this. DNR for the MX alternative exceeds the MC alternative by $409,000. Of this difference, 92 percent is due to the $378,000 lower discounted total transportation cost of the MX alternative. This lower discounted transportation cost is due to the selection and timing of units to be harvested, as well as transportation selections within the network itself.

The relative levels of harvest and road construction across the four approaches were about the same in Series II (fig. 14) as in Series I. In Series II the same harvest units were selected in the FX, VR, and MC alternatives, so that the differences in DNR among them are due to differences in transportation costs. Also, the MX approach again indicated less timber harvest and road construction in time period 1 and more in time period 3. It is interesting that a smaller percentage of the increase in DNR in the MX alternative relative to the other alternatives is due to a smaller discounted transportation cost for the MX alternative. In this series the difference in DNR between the MX and MC alternatives is $543,000, while the difference in discounted transportation cost is $351,000. The reduction in transportation cost represents only 65 percent of the increase in DNR (as opposed to 92 percent in Series I). In other words, in Series II, selecting units with higher net values represents a greater proportion of the increase in DNR than in Series I, where selecting units which held down transportation cost was more important.

Table 2.—Indicated net stumpage values for Twin Rocks by analysis approach, time period, and series

Series and time period	Analysis approach			
	FX	VR	MC	MX
	Thousands of dollars			
Series I				
Time period 1	-330	-148	-111	440
Time period 2	88	87	94	27
Time period 3[1]	1,692	1,692	1,698	1,702
Series II				
Time period 1	-289	-107	-96	520
Time period 2	52	52	55	34
Time period 3	1,294	1,283	1,312	1,391

[1]Time period 3 presented on an averaged decade basis.

Indicated net stumpage values for the Twin Rocks alternatives are presented in table 2. Indicated net stumpage values differ from DNR in two ways: (1) agency costs for sale preparation and administration and silvicultural exams are not included, and (2) they are undiscounted. Net stumpage value compares the estimated value of timber to the costs that value must cover for timber to sell, assuming all roads are to be financed with purchaser road credits. In other words, it measures the sale viability of the activities within each time period.

The FX, VR, and MC alternatives all have negative indicated net stumpage values in the first time period in both Series I and II. This indicates that some of the roads to be constructed in time period 1 would have to be financed with capital investment (budgeted) dollars. More precisely, the time period 1 activities for one of these alternatives could be packaged as one sale or several sales, but regardless, some capital investment dollars would be required for all the time period 1 activities to be accomplished. The positive indicated net stumpage values for the MX Series I and II alternatives, and time periods 2 and 3 for the FX, VR, and MC alternatives, indicate the activities in those time periods can be accomplished without financing roads with budgeted dollars.

Copeland Creek Area.—The Series I results for Copeland Creek are presented in figure 15. Each of the approaches recognized that, given the assumed growth rates for timber and the real changes in prices and costs, it was most efficient to harvest in time periods 2 and 3. As on Twin Rocks, the same units were selected for harvest in the FX, VR, and MC alternatives. Among these alternatives, the miles of road to be constructed decreased from FX to VR to MC in time period 2 and increased in time period 3. The road construction costs have about the same percentage change across approaches, indicating the lower costs are not a result of selecting lower cost roads, but rather simply fewer miles for construction. Haul cost was virtually the same for each of these three alternatives. The net result is a discounted total transportation cost difference between FX and VR of $59,000 and between VR and MC of only $6,000.

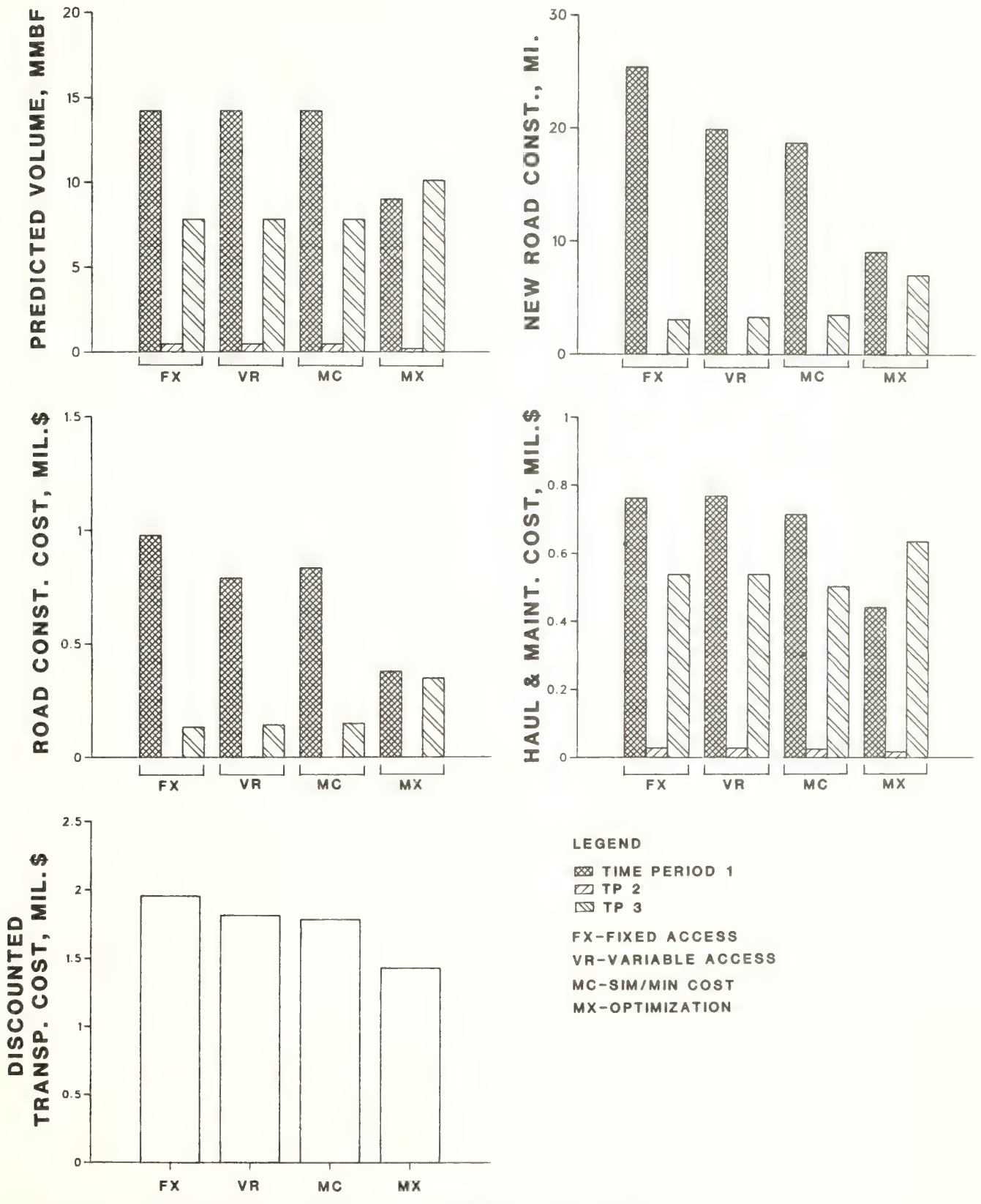


Figure 14.—Items of interest for the Twin Rocks Series II alternatives. (Time period 3 is presented on an averaged decade basis.)

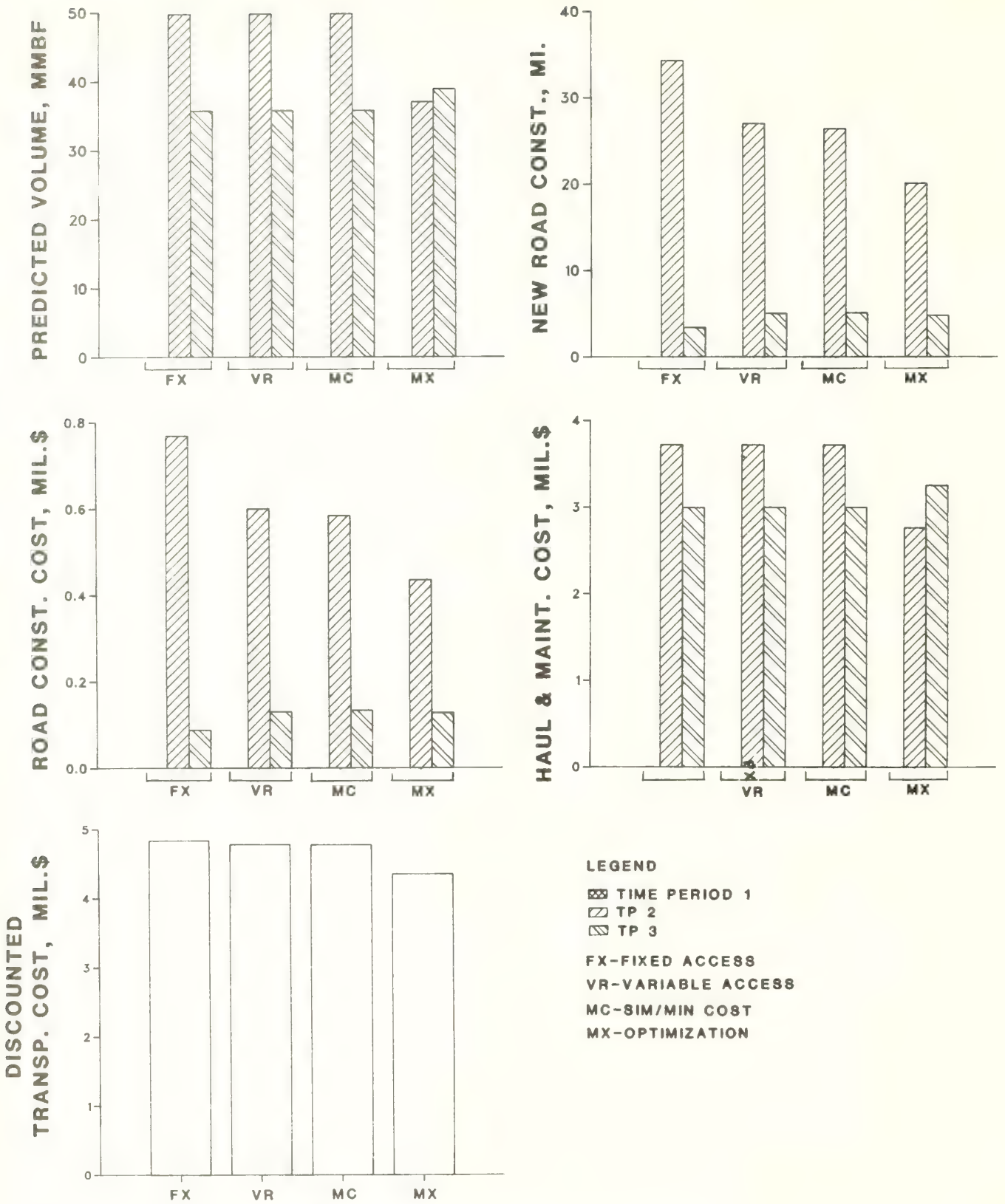


Figure 15.—Items of interest for the Copeland Creek Series I alternatives. (Time period 3 is presented on an averaged decade basis.)

The MX alternative differed from the first three in that it would harvest less timber in the second decade, but more per decade in time period 3. Note, however, that all four alternatives would harvest about the same total quantity over the 50-year planning horizon.

The MX alternative would also construct fewer miles of road in time period 2 than the other approaches and about the same per decade in time period 3. This results in a discounted total transportation cost that is $423,000 less than the MC alternative. This savings accounts for about 42 percent of the difference in DNR between these two alternatives. As for Twin Rocks, this decrease in total transportation cost is due to the selection of units for harvest as well as road construction selections themselves.

In Series II (fig. 16), all four approaches again developed alternatives with harvesting in only time periods 2 and 3. There were no differences in the units selected for harvest among the FX, VR, and MC alternatives and almost no differences in the road links selected for construction. There were some interesting differences regarding the MX alternative, however. Total timber harvest for this alternative is larger in both time periods 2 and 3. As opposed to what was observed in Series I and on Twin Rocks, the MX alternative would construct more miles of road in time period 2 and fewer in time period 3. The road construction costs for MX, relative to the other approaches, reflect these mileage differences. The discounted total transportation cost for the MX alternative is higher than the MC alternative by $382,000. Yet DNR for the MX alternative exceeds the MC alternative by $1.2 million. The MX approach was able to harvest a larger quantity of timber while satisfying the Series II sediment and water objectives.

The indicated net stumpage values (table 3) for the alternatives developed by all four approaches are positive in each time period in both Series I and II. This indicates that the aggregate of the activities within each time period is likely to be financially viable.

Table 3.—Indicated net stumpage values for Copeland Creek by analysis approach, time period, and series

Series and time period	Analysis approach			
	FX	VR	MC	MX
	-- Thousands of dollars --			
Series I				
Time period 1	—	—	—	—
Time period 2	1,149	1,318	1,333	1,270
Time period 3[1]	4,837	4,792	4,789	6,030
Series II				
Time period 1	—	—	—	—
Time period 2	806	806	806	1,253
Time period 3	4,604	4,604	4,621	6,016

[1]Time period 3 presented on an averaged decade basis.

Pot Mountain Area.—The factors for Series I are presented in figure 17. As was the case on Copeland Creek, there were no differences in the units selected for harvest among the FX, VR, and MC alternatives, and very few differences in the road links selected for construction.

Major differences did occur between the MX and other alternatives. The MX alternative would harvest substantially more timber. The greatest increase would occur in time period 2, where the FX, VR, and MC alternatives would harvest only 0.6 million bd ft, while the MX approach would harvest 79.0 million bd ft. The MX alternative also indicated substantially more road construction in time periods 1 and 2 (less in time period 3), with a discounted total transportation cost almost twice that of the other alternatives. The net effect is a DNR for the MX alternative of $15.0 million, versus about $10.8 million for the other alternatives.

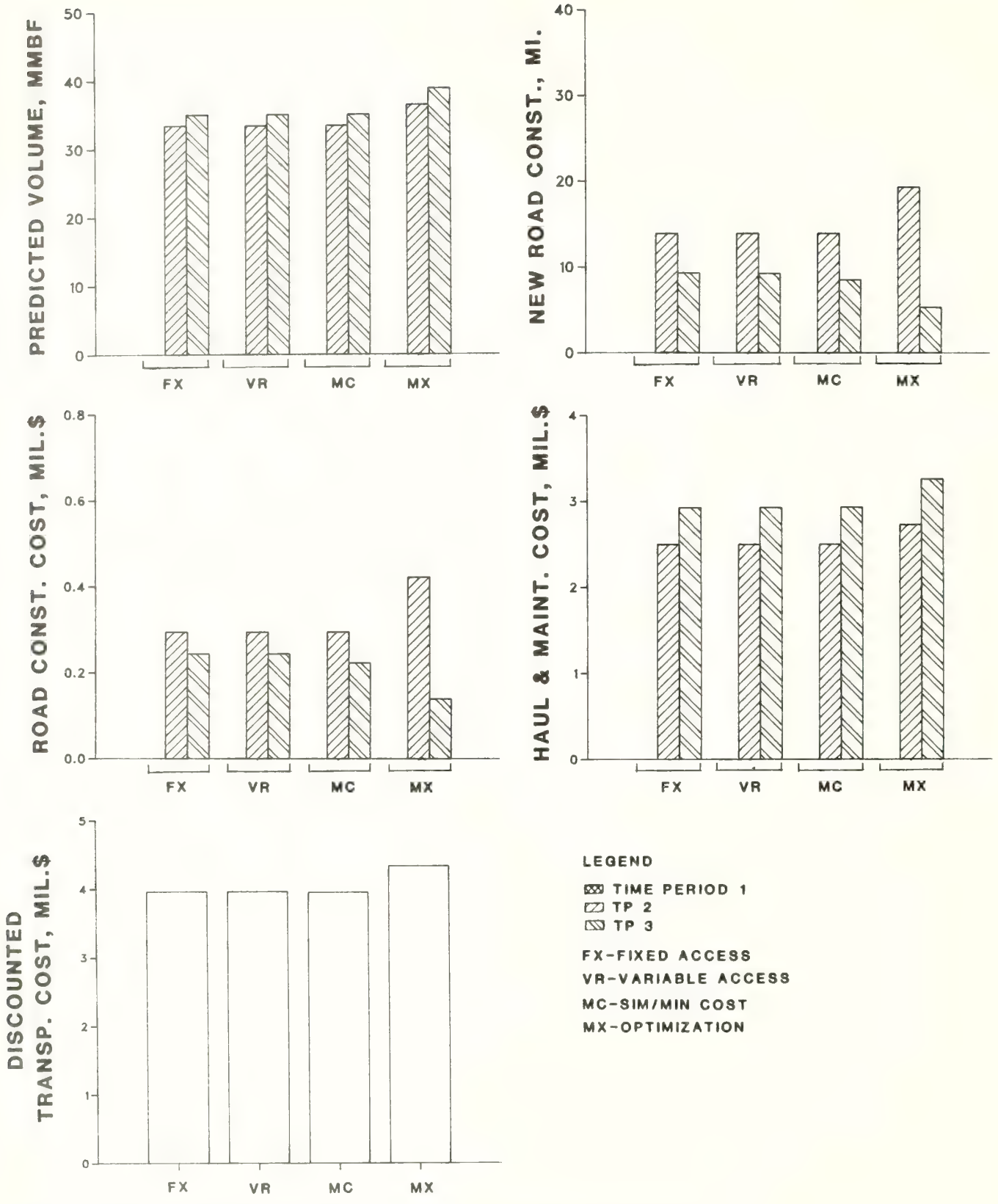


Figure 16.—Items of interest for the Copeland Creek Series II alternatives. (Time period 3 is presented on an averaged decade basis.)

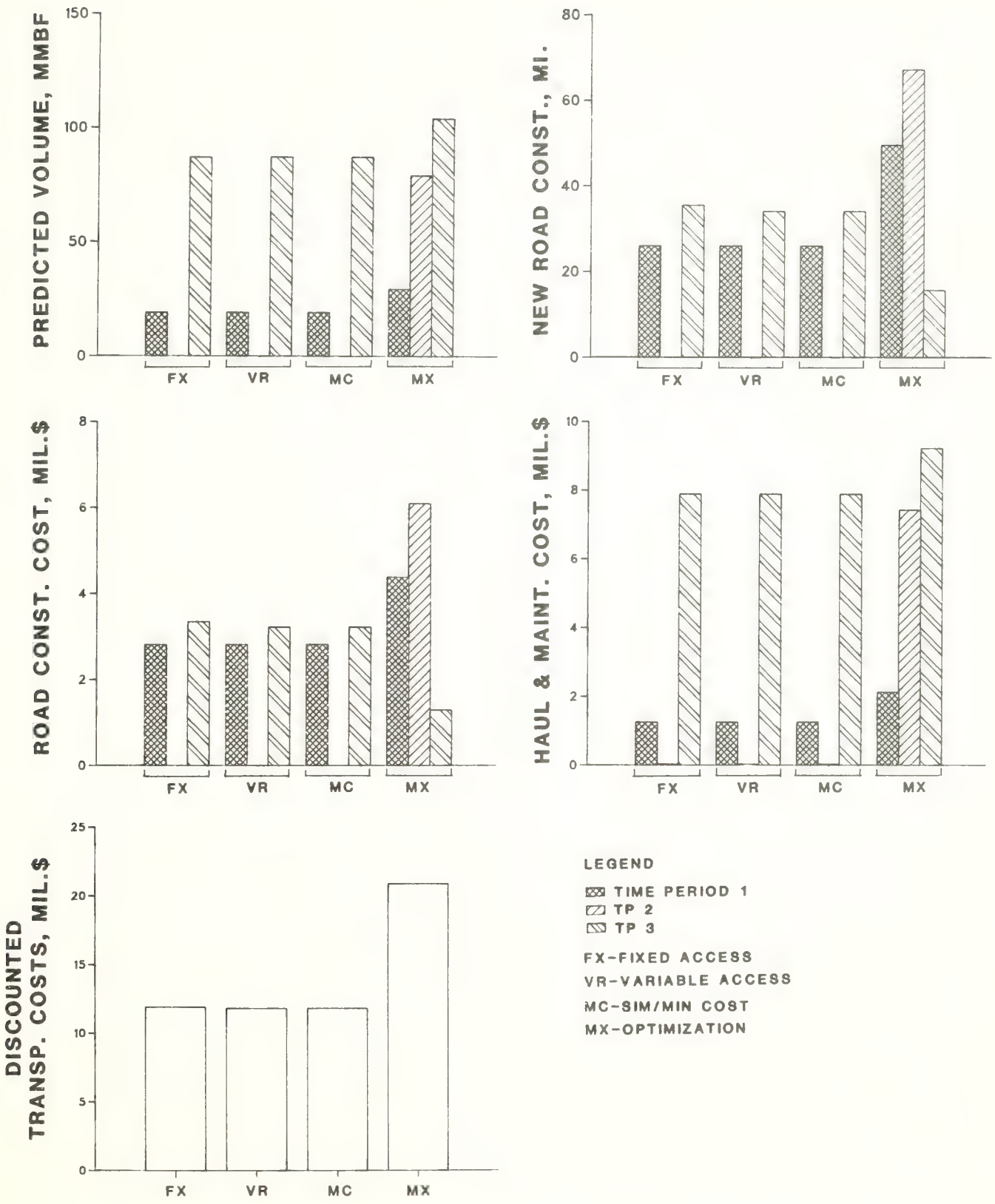


Figure 17.—Items of interest for the Pot Mountain Series I alternatives. (Time period 3 is presented on an averaged decade basis.)

The Series II nontimber objectives for Pot Mountain were substantially more restraining than on the other two test areas. The main route of haul selected for the FX approach could not be constructed into the interior of the Pot Mountain area (where the majority of the current mature timber exists) within one decade. The difficulty was that too much sediment would be created in one of the critical drainages. The solution was to construct this road over two decades, thereby spreading out the impact of sedimentation. As a result, no timber harvests would occur in the FX alternative until time period 2 (fig. 18). Different routes were used in the other alternatives to access the mature timber in time period 1. These routes had somewhat higher costs but satisfied the sediment objectives.

There were some minor differences in the road links selected for construction between the VR and MC alternatives. The latter would construct about a mile less in time period 1, a mile more in time period 2, and 1.5 miles less in time period 3. The net effect was a discounted total transportation cost of $87,000 less for MC, representing the total difference in DNR between these alternatives. Relative to the FX alternative, they had a discounted total transportation cost on the order of $1.3 million more. This higher cost was offset by higher total timber values. DNR for the VR alternative exceeds the FX alternative by $28,000.

The Series II MX alternative would harvest substantially more timber and construct substantially more miles of road than the first three alternatives, while still satisfying the sediment and cover/forage objectives. The major difference in timber harvest would occur in time period 2. Road construction for the MX alternative was somewhat higher in time period 1, substantially higher in time period 2, but less in time period 3. Discounted total transportation cost for the MX alternative is about $5.6 million greater than the VR and MC alternatives and about $7 million greater than the FX alternative. The net effect is a DNR for MX of $10.9 million versus $7.3 to $7.5 million for the other alternatives.

Finally, it is noteworthy that the indicated net stumpage value (table 4) is negative for the first entry in each of the alternatives developed for Pot Mountain. To a large extent, this is due to the amount of road which must be constructed to access the mature timber in this area. Thus, even though the large positive DNR values indicate harvesting in the area is profitable, there is predicted to be a cash-flow deficit in time period 1.

Table 4.—Indicated net stumpage values for Pot Mountain by analysis approach, time period, and series

Series and time period	Analysis approach			
	FX	VR	MC	MX
	Thousands of dollars			
Series I				
Time period 1	−136	−136	−136	−933
Time period 2	42	42	42	4,702
Time period 3[1]	16,646	16,755	16,755	21,726
Series II				
Time period 1	−151	−793	−720	−1,186
Time period 2	−1,037	−152	−239	1,819
Time period 3	12,436	12,714	12,813	17,725

[1]Time period 3 presented on an averaged decade basis.

The Pot Mountain area illustrates a point made in a recent publication dealing with the below-cost timber sale issue (Schuster and Jones 1985). Because of the upfront road construction cost, the activities in the first time period would give rise to a below-cost timber sale if packaged as one sale; that is, the net cash-flow in that time period is negative. Yet, the large positive overall DNR's for the area (for the MX alternatives overall DNR is $15.0 million for Series I and $10.9 million for Series II) indicate the long-run economic returns from timber management are favorable. Eliminating the negative cash-flow in time period 1 by either harvesting more timber in that time period or by postponing harvest until a later time would result in lowering the overall DNR for the area.

Equal Harvest Volume Alternatives.—The overall DNR per acre for the MX alternatives exceeded the DNR's for the other approaches by a substantial margin on each of the three test areas. An obvious question at this point is, "How much of this increase in DNR is due to differences in the quantities harvested across time periods?"

To investigate this question, another MX alternative, called the equal volume MX alternative, was developed for each of the three areas. In these alternatives, the optimization models were required (through constraints) to harvest the same quantities of timber in each time period as the Series II VR and MC alternatives. In addition, the other Series II management objectives listed earlier in table 1 were required to be met as well.

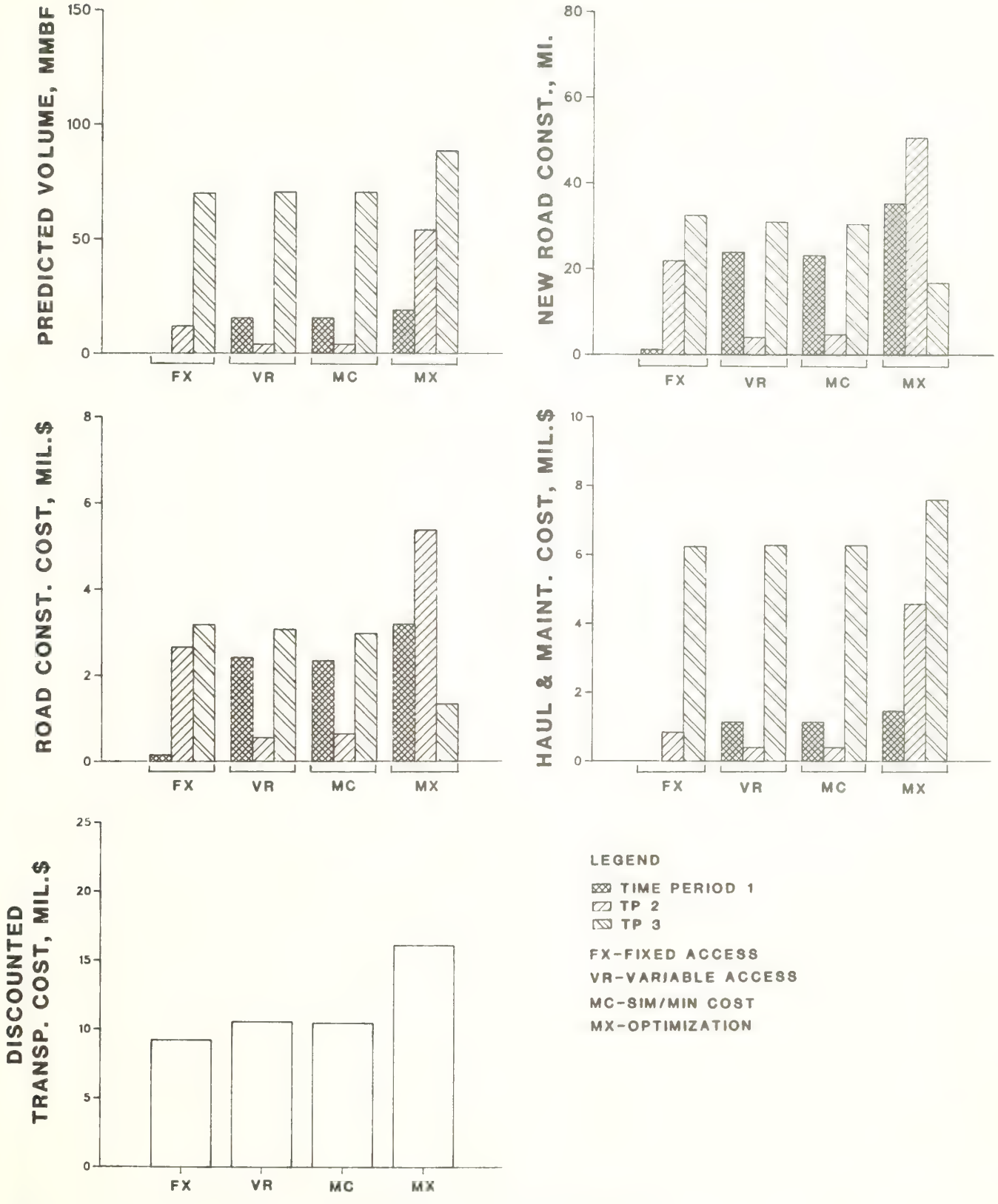


Figure 18.—Items of interest for the Pot Mountain Series II alternatives. (Time period 3 is presented on an averaged decade basis.)

The results from the Twin Rocks equal volume MX alternative are presented along with the Series II results for FX, VR, and MC in figure 19. DNR per acre for the equal volume MX is $177, $26 less than the Series II MX, but still $71 more than the Series II VR alternative.

As was the case for the Series II MX alternative, the new MX alternative would construct fewer miles of new road in time period 1 and slightly more miles in time period 3 than the other three approaches. Largely as a result of fewer miles to construct, road construction cost in time period 1 for the equal volume MX alternative is less than the other approaches. Haul cost for the MX approach is also less. The difference in total transportation cost between the equal volume MX alternative and the other alternatives accounts for 41 percent of the difference in DNR between VR and MX, and 35 percent of the difference in DNR between MC and MX. The balance of the differences in DNR is due to choice of units for harvest to attain the specified levels of harvest in each time period.

For Copeland Creek, DNR per acre for the new MX alternative decreased only $7 from the Series II MX alternative (from $492 per acre to $485 per acre). Road construction mileage and cost are higher in time period 2 for the equal volume MX alternative than the other approaches presented in figure 20, but are lower in time period 3. Haul cost is essentially the same for each of the four alternatives. The resulting difference in discounted total transportation cost between the new MX alternative and the other alternatives accounts for only about 1 percent of the difference in DNR between the new MX and other alternatives. In other words, essentially all of the increase in DNR for the equal volume MX alternative (relative to the other approaches) is due to the units selected for harvest to achieve the same harvest volumes.

DNR per acre for the equal volume MX alternative on Pot Mountain is $338, a decrease of $84 from the Series II MX solution (fig. 21). DNR per acre for the new MX alternative does, however, exceed the Series II VR alternative by $54 and the Series II MC alternative by $50. Miles of new road construction is slightly greater in time period 1 but considerably less in time period 3 for the new MX alternative than the VR or MC alternatives (recall the harvest schedule for the Series II FX alternative was substantially different from the VR and MC alternatives on the Pot Mountain area). Road construction cost for the new MX alternative, however, is slightly less than for VR in time period 1 and is significantly less than both VR and MC in time period 3. In addition, haul cost for the new MX alternative is somewhat less in both time periods 1 and 3. The resulting difference in discounted total transportation cost between the new MX alternative and the Series II VR alternative accounts for 36 percent of the difference in DNR between these alternatives. Thirty-three percent of the difference in DNR between the MX and MC alternatives is explained by the difference in discounted transportation cost between these alternatives. Thus, as was the case on the first two test areas, the majority of the difference in DNR between the equal volume MX alternative and the other approaches can be traced back to the selection of units for harvest to meet the stated harvest objectives.

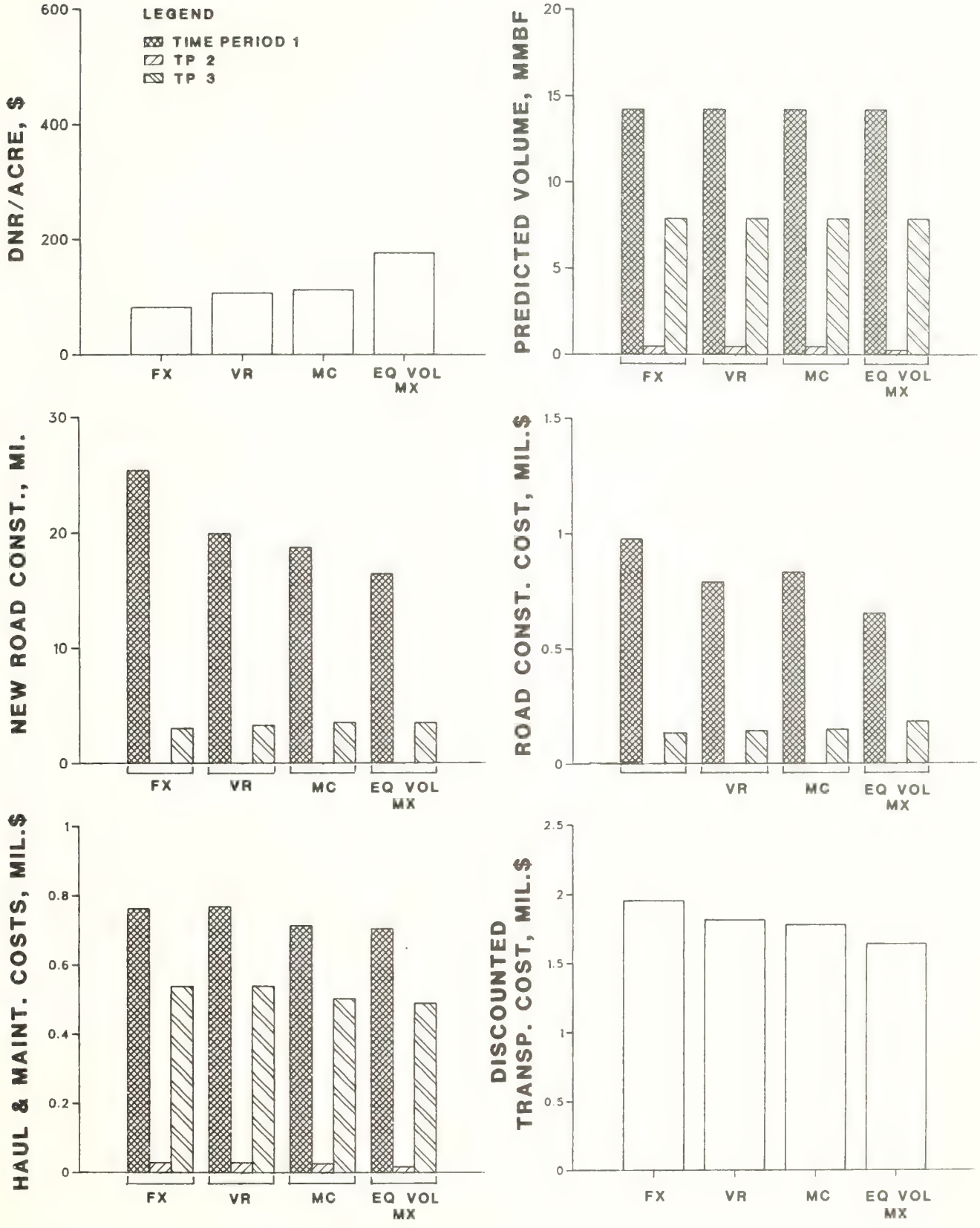


Figure 19.—The equal volume MX alternative compared to the Series II FX, VR, and MC alternatives for Twin Rocks.

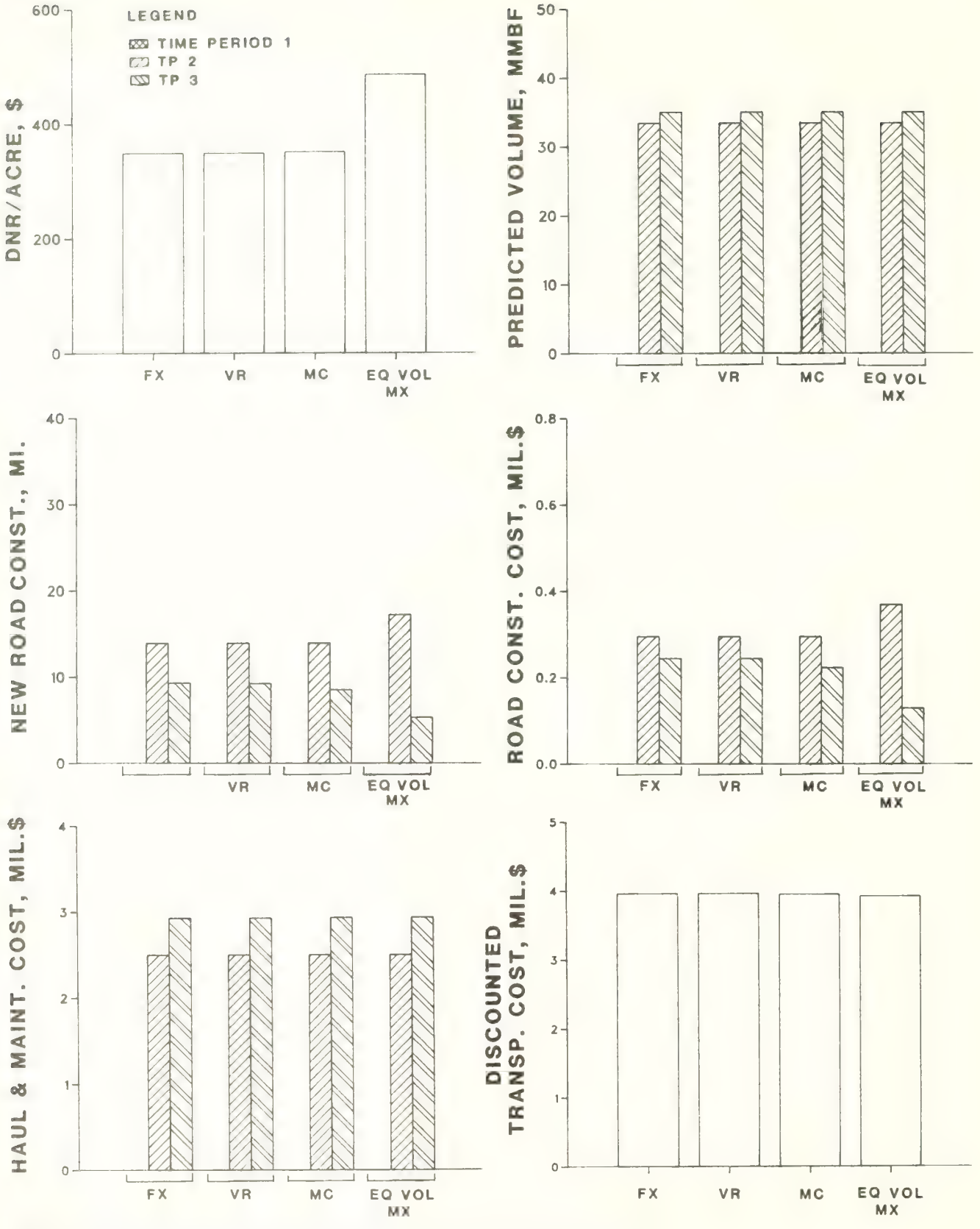


Figure 20.—The equal volume MX alternative compared to the Series II FX, VR, and MC alternatives for Copeland Creek.

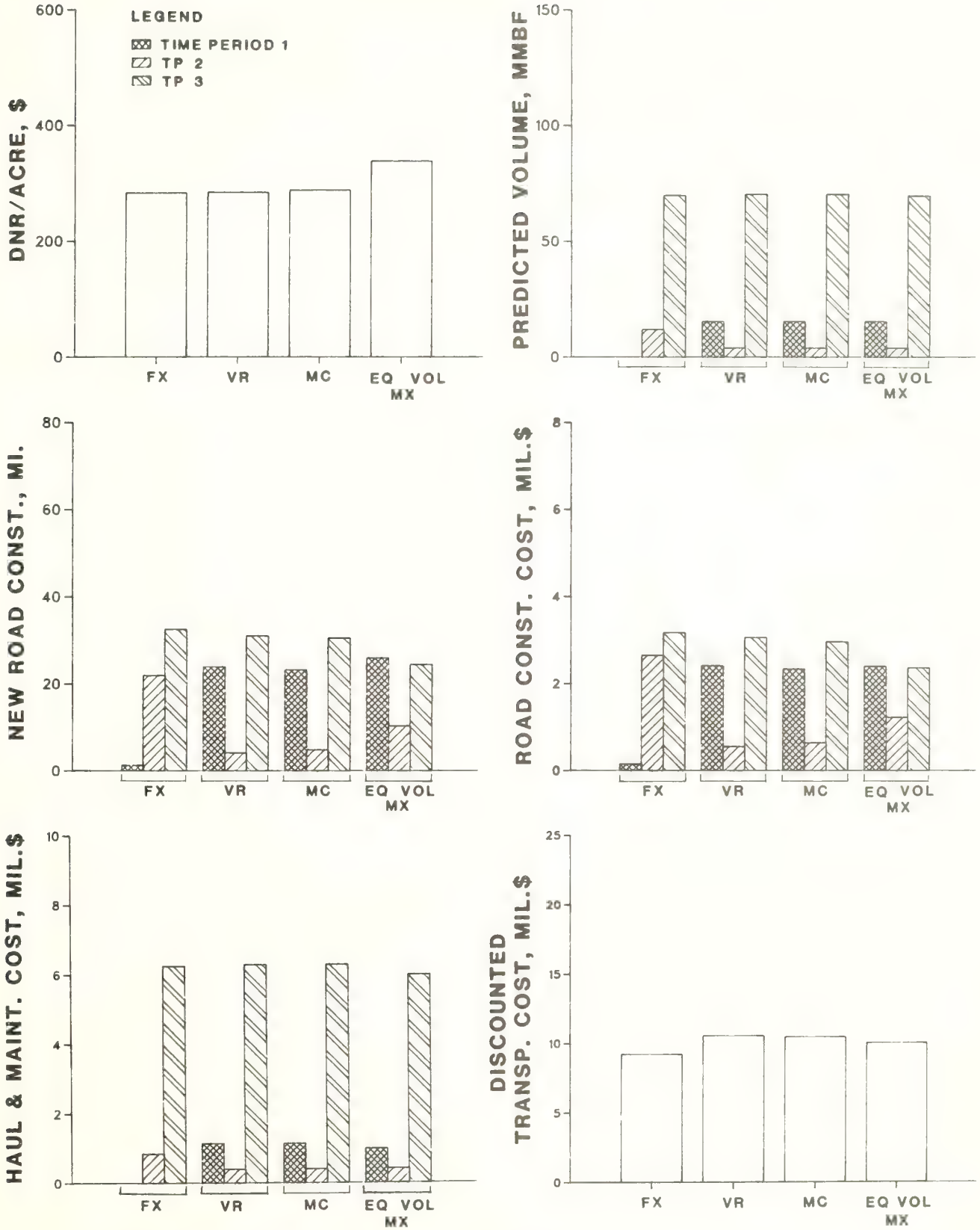


Figure 21.—The equal volume MX alternative compared to the Series II FX, VR, and MC alternatives for Pot Mountain.

The final topic of interest regarding the equal volume MX alternatives is the indicated net stumpage values presented in table 5. For Twin Rocks, the critical indicated net stumpage values are in time period 1 where they were negative for FX, VR, and MC in both Series I and II. Indicated net stumpage for the equal volume MX alternative decreased only slightly from Series II MX (from $520,000 to $483,000). This value exceeds the negative values for FX, VR, and MC by a half million dollars or more.

For Copeland Creek, indicated net stumpage values for all the Series I and II alternatives indicated the activities in each time period can be accomplished without financing roads with budgeted dollars (all indicated net stumpage values were large positive numbers). This trend continued in the equal volume MX alternative, where indicated net stumpage values in both time periods 2 and 3 decreased only slightly from the Series II MX alternative.

Table 5.—Indicated net stumpage value for the equal volume MX alternatives and the Series II FX, VR, and MC alternatives

Area and time period	Analysis approach			
	Series II			Equal volume
	FX	VR	MC	MX
	Thousands of dollars			
Twin Rocks				
Time period 1	−289	−107	−96	483
Time period 2	52	52	55	36
Time period 3[1]	1,294	1,283	1,312	1,275
Copeland Creek				
Time period 1	—	—	—	—
Time period 2	806	806	806	1,173
Time period 3	4,604	4,604	4,621	5,863
Pot Mountain				
Time period 1	−151	−793	−720	−454
Time period 2	−1,037	−152	−239	−491
Time period 3	12,436	12,714	12,813	14,418

[1]Time period 3 presented on an averaged decade basis.

On Pot Mountain, negative indicated net stumpage values were observed in Series II in both time periods 1 and 2 in all alternatives but the MX alternative, which had a positive value in time period 2 (even though each had overall DNR's exceeding $7 million). Relative to Series II MX, indicated net stumpage for the equal volume MX alternative increased from −$1,186,000 to −$454,000, but in time period 2, decreased from +$1,819,000 to −$491,000.

Required Resources

The same data were used for each approach within a test area. Table 6 presents the number of person-days spent supplying data for the test models. Total time is the sum of three categories: network and road projects (which includes developing a log-flow plan); potential harvest units and the associated harvest alternatives; and the yield, cost, and price information. On a per-1,000-acre basis (for areas having harvesting alternatives) number of person-hours ranged from a low of 2.7 for Copeland Creek to 8.1 for Twin Rocks. Several reasons explain at least some of this time difference. Twin Rocks was the first test area. Here, more effort was devoted to deciding what data were needed, how precise the data should be, and so on. For example, the decision to delineate land into operable potential harvesting units was not made until after work on Twin Rocks was begun. In a very real sense, Twin Rocks served as the testing ground for developing the approaches that were applied on the other two areas.

The smaller amount of time devoted to Copeland Creek data is at least partially explained by the fact that a substantial amount of harvesting activity had occurred in the area in the past and about 40 percent of the road network had already been constructed. Also, the relationships for predicting sediment and water yield that had been used on Twin Rocks were modified only slightly for use on Copeland Creek (a totally different approach was used for estimating sediment for Pot Mountain).

Table 6.—Person-days of National Forest System personnel time devoted to supplying data for the test area

	Twin Rocks	Copeland Creek	Pot Mountain
	Person-days		
Network and road construction alternatives	23	10	90
Potential harvest units and alternatives	20	11	40
Yield, cost, and price information	5	2	15
Total time	48	23	145
Time per 1,000 acres with harvest alternatives	8.1	2.7	5.6

In addition to the data preparation task listed in table 6, the MX approach also required identifying the adjacent units for implementing the adjacency rule. In this approach the adjacency rule had to be expressed mathematically, whereas in the other approaches it was implemented by not allowing the cooperating analysts to choose adjacent units. Identifying and recording adjacent units took about 5 person-days each for Twin Rocks and Copeland Creek, and about 12 person-days for the somewhat larger Pot Mountain area.

Once assembled, data were entered into the computer. As stated earlier, IRPM software was used in all four approaches. The IRPM data input process allows for a high degree of flexibility in constructing models, but is extremely labor intensive. Because of this, several computer programs were written that read the data prepared by the cooperating National Forest System personnel and that wrote card images in IRPM format. Once these programs were written and debugged, entering and checking data and generating the linear programming model took about 10 person-days for Twin Rocks and Copeland Creek, and about 15 person-days for Pot Mountain.

It is difficult to predict the resources required for applying each of the four approaches in an operational setting. We have first-hand experience in operating only IRPM and the related software that was used to accomplish each of the four approaches. Second, resource requirements would be expected to depend somewhat on the specific software that would be used for each approach. We can, however, make a few general observations.

First, each of the four approaches requires the same basic data, with one exception—the MX approach, which requires developing mathematical relationships for the adjacency rule described earlier. There is a large range in the quality of data that could be used to conduct ALA, and a corresponding wide range in the cost and time required to prepare those data. The number of person-days reported in table 6 are likely representative of time required for developing data of a similar quality and type for other areas. This includes networks of the type currently used in area transportation planning, delineating an area into potential harvesting units, and developing fairly specific road construction and harvesting activities. Perhaps more time could be profitably spent in developing the yield, cost, and price relationships and data, because once developed the information could be applied over more than one area.

On many National Forests, networks similar to those used in this study are commonly developed in area transportation planning. Thus, applying the approaches described in this study would mainly require additional data for delineating potential harvest units and developing the harvesting alternatives. Portions of the yield, cost, and price information would also require additions to current procedure. But, once developed, these relationships could likely be applied on other areas within a Ranger District with little or no modification.

Significant labor savings may be possible if a data-digitizing system were to be used to enter road link and potential harvest unit data. This would make it possible to calculate electronically such things as length of road links and acreage of potential harvest units. Digitized data would also streamline plotting the geographic location of road construction and harvest activities selected in an alternative for area management.

There are some significant differences in computer resources required among the four approaches. The simulation approaches could conceivably be operated on a microcomputer and certainly on a minicomputer such as the Data General equipment owned by the Forest Service.

The MC approach is somewhat more demanding of processing equipment because of the need to include a routine that minimizes discounted transportation cost. Some of the transportation cost minimization programs operate on large, mainframe computers such as the USDA Fort Collins Computer Center, for example, TRANSHIP (Kirby and others 1981a), Timber Transport Model (Sullivan and Barnes 1980), and MINCOST (Schnelle 1977). But, at least one program, NET4T (Sessions 1985), is reported to operate on small computers.

The MX approach is the most demanding of computer resources of the four approaches. For the near future, it almost certainly would require a mainframe computer system. Cost for developing an alternative using the MX approach on Twin Rocks and Copeland Creek ranged between $35 and $55 (using T priority at the Fort Collins Computer Center). Cost for Pot Mountain was somewhat larger, $140 to $200 per MX alternative, because the model for this area was substantially larger (roughly 6,000 rows and columns versus about 2,000 rows and columns for the Twin Rocks and Copeland Creek models).

CONCLUSIONS

The purpose of this study was to compare four analytical approaches for use in integrated area level analysis. The objective for each approach was to develop the management alternative that has the highest DNR possible, while satisfying the Series I and Series II management objectives. DNR was chosen because it is a good measure of management efficiency (an alternative that gives rise to the highest DNR while satisfying the other management objectives is efficient). It is believed that comparing other possible objectives to be maximized or minimized (timber volume per some specified period of time, discounted total cost) would result in similar relative differences.

Significant differences were found among the alternatives developed using the four approaches. One major difference was that the DNR's associated with the MX alternatives were significantly higher than the DNR's for the alternatives developed by the other three approaches. This difference was statistically significant at the 95 percent confidence level. The average difference in DNR between the MX and MC approaches (MC was the approach with the next highest average DNR) was $119 per acre. This amounts to an average difference in DNR on the order of $1.2 million on an area having 10,000 acres with harvest alternatives in a 50-year planning horizon.

The difference in efficiency between the MX and other approaches appears to be larger the more complex the planning problem. The percentage of the MX DNR achieved by the other approaches was significantly lower (95 percent probability level) for the relatively more complex Series II planning problems than for Series I. Further, the percentage of the MX DNR achieved by the other approaches was significantly lower (95 percent confidence level) for the Twin Rocks area. The Twin Rocks area had a grid-shaped road network, which was more complex from a transportation standpoint than the Copeland Creek and Pot Mountain networks.

There were no statistically significant differences among the DNR's associated with the alternatives developed by the FX, VR, and MC approaches. Differences in DNR for these three approaches are hardly perceptible in figure 10 for Copeland Creek and Pot Mountain. On Twin Rocks, however, the differences in DNR for these three alternatives were somewhat larger. In Series II, the DNR for FX was 41 percent of the MX alternative, while MC was 55 percent, a $30 per acre difference. This suggests that statistically significant differences could exist among these three approaches when the transportation aspect of area-level analysis is complex. Unfortunately, this study did not have a sufficient number of areas to test this hypothesis.

The differences found between the MX and the other approaches were not consistent from one area to the next. On Twin Rocks, the MX alternatives tended to defer more timber harvest and road construction from time period 1 to time period 3 in both Series I and II. The same relative pattern occurred in Series I on Copeland Creek, except here the harvesting and road construction were deferred from time period 2 to time period 3. In Series II, however, the pattern reversed—the MX alternative would harvest more timber and construct more miles of road in time period 2. For Twin Rocks and Copeland Creek, although the timing of harvest varied, each approach within a series would harvest roughly the same quantity of timber over the five-decade planning horizon. In contrast, on Pot Mountain, the MX alternative would harvest substantially more timber and construct substantially more miles of road over the planning horizon.

These differences are the result of differences in timber growth rates, the spatial location of potential roads and harvest units, and differences in costs and delivered log prices and how they are assumed to change over time.

An additional MX alternative was developed for each test area to determine how much of the difference in DNR between the Series II MX alternatives and the other approaches was due to differences in harvest scheduling. For these solutions, the optimization models were forced to harvest the same quantities of timber per time period as the Series II VR and MC approaches, as well as satisfy the other Series II objectives.

Significant differences in DNR per acre were also found between these new MX alternatives and the Series II VR and MC alternatives. These differences averaged $86 per acre between the new MX alternatives and the Series II VR alternatives and $82 between the new MX alternatives and the Series II MC alternatives.

The study provides much less information about the resources required by each of the four approaches, largely because the tests involved generic categories of analysis, not computer software. Several observations can, however, be made:

1. Under the general formulation used in this study (potential harvesting units and proposed road links), each of the four approaches requires essentially the same data. The only difference is the adjacency relationships required for the MX approach. There could, however, be major differences in the ease and efficiency of data entry processes among computer software packages, even within one of our approach categories.

2. Once data are entered, substantially more calculations are made in the MX approach than in the simulation approaches. As a result, the MX approach requires more computer resources and computer expertise among the users. Based on our experience, computer costs could be expected to range from $30 to $250 per area-level analysis alternative. This additional cost could, however, be rather modest when compared to data preparation and entry costs associated with each approach.

3. Resources required for an MC approach could vary considerably, depending on the computer routine used to minimize discounted total transportation cost. Some routines for minimizing transportation cost require a large computer system. For them, the resources required would be expected to be similar to the MX approach. But at least one routine for minimizing transportation cost (Sessions 1985) is reported to operate on small computers. Resources required if this were integrated into an MC system would be expected to be similar to the FX and VR approaches.

In area-level analysis, rational choice among analysis approaches involves a comparison of costs and benefits of each approach. The DNR's associated with the test applications in this study indicate the net timber benefits provided by the approaches. Unfortunately, the study was not able to provide comparable estimates of the resources required for implementing each of these approaches. In view of this fact, comparing these approaches via a break-even analysis based on difference in measured benefit (DNR) would seem appropriate. To illustrate, the average difference in DNR per acre between the MX and MC approaches was $119 per acre, or $1.19 million for a typical 10,000-acre area. This means that up to $1.19 million **more** could be spent conducting an MX analysis before one would be indifferent in choosing between the MX and MC approaches. If the cost of conducting an MX approach were to exceed the cost of implementing the MC approach by more than $1.19 million, then the MC approach would be preferred. Similar break-even points could be calculated for comparisons among the other approaches.

REFERENCES

Kirby, M. E.; Wong, P.; Hager, W. A. Guide to the TRANSHIP model. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Management Sciences Staff; 1981a. 161 p.

Kirby, M. E.; Wong, P.; Hager, W. A.; Huddleston, M. E. Guide to the integrated resource planning model. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Management Sciences Staff; 1981b. 212 p.

Johnson, K. Norman. [Personal communication]. 1985 May 7. Fort Collins, CO.

Schnelle, W. F. A brief guide to "MINCOST" (CSSG*RILIB.MINCST2). Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region Engineering; 1977. 13 p.

Schuster, E. G.; Jones, J. G. Below-cost timber sales: analysis of a policy issue. General Technical Report INT-183. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1985. 17 p.

Sessions, John. Network analysis using microcomputers for logging planning. Corvallis, OR: Oregon State University, Department of Forest Engineering; 1985. 5 p.

Sullivan, E.; Barnes, B. Timber Transport Model, Version 2.0. Research Report UCB-ITS-RR-79-18. Berkeley, CA: University of California; 1980. 167 p.

U.S. Department of Agriculture, Forest Service. Project Area Scheduling System (PASS) users guide 2.00. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region; 1985. 98 p.

U.S. Department of Agriculture, Forest Service. Procedure for obtaining a heuristic solution to IRPM/TRANSHIP problems. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Management Sciences Staff; 1983. [Number of pages unknown].

U.S. GOVERNMENT PRINTING OFFICE: 1985-0-676-039/20033

Jones, J. Greg; Hyde, James F. C., III; Meacham, Mary L. Four analytical approaches for integrating land management and transportation planning on forest lands. Research Paper INT-361. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 33 p.

Four approaches for analyzing site-specific transportation systems and timber harvesting alternatives on small areas were tested on three planning areas. The approaches ranged from a rather simple simulation to optimization. The same data were used for each approach on an area. The optimization approach resulted in significantly higher discounted net revenues (95 percent confidence level) than plans developed by the other approaches when management objectives were identical.

KEYWORDS: area-level analysis, integrated transportation planning, network analysis, timber management, land management planning

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station
Ogden, UT 84401**

Research Paper
INT-362

April 1986

Aspen Community Types of Utah

**Walter F. Mueggler
Robert B. Campbell, Jr.**

CLEMSON UNIVERSITY
AUG 29 1986

THE AUTHORS

WALTER F. MUEGGLER is principal plant ecologist and was leader of the Intermountain Research Station's Aspen Ecology and Management Research Work Unit at Logan, UT. He has been involved with research on aspen lands for over 10 years. He holds a B.S. degree in forestry from the University of Idaho, M.S. degree from the University of Wisconsin, and Ph.D. in plant ecology from Duke University.

ROBERT B. CAMPBELL, JR. was a botanist with the Intermountain Research Station's Aspen Ecology and Management Research Work Unit in Logan, UT. He began working in aspen-related research for the Station in 1974. He has a B.S. degree in botany from Brigham Young University and a B.S. degree in agronomy from Utah State University.

RESEARCH SUMMARY

A vegetation classification for the aspen-dominated forests of Utah is based upon existing community structure and plant species composition. Included are 36 community types that occur within six cover-type categories. A diagnostic key using indicator species facilitates field identification of the community types. Vegetational composition, productivity, and successional status are included. Tables provide detailed comparisons of community types. The classification and descriptions are based upon data from over 1,200 aspen stands scattered across the six National Forests within Utah.

ACKNOWLEDGMENTS

Assistance in collecting field data was provided by summer technicians Kevin Gardner and Elizabeth Cole. Some stand data related to separate studies on aspen to conifer succession were furnished by Roy Harniss (Intermountain Research Station) and Ronald Mauk (Utah State University). The computer programs used to prepare synthesis and summary tables essential to development of the classification were written by Ronald Mauk.

CONTENTS

Page

Introduction 01
Methods 03
Field Methods 03
Data Analysis 04
Other Considerations 07
The Classification: Vegetation Key 08
Type Descriptions 13
Populus tremuloides/Acer grandidentatum/Pteridium aquilinum c.t. 13
Populus tremuloides/Prunus virginiana/Senecio serra c.t. 14
Populus tremuloides/Prunus virginiana/Carex geyeri c.t. 15
Populus tremuloides/Sambucus racemosa c.t. 15
Populus tremuloides/Symphoricarpos oreophilus/Senecio serra c.t. 16
Populus tremuloides/Symphoricarpos oreophilus/Carex geyeri c.t. 17
Populus tremuloides/Symphoricarpos oreophilus/Festuca thurberi c.t. 18
Populus tremuloides/Juniperus communis/Carex geyeri c.t. 18
Populus tremuloides/Juniperus communis/Sitanion hystrix c.t. 20
Populus tremuloides/Symphoricarpos oreophilus/Bromus carinatus c.t. 20
Populus tremuloides/Symphoricarpos oreophilus/Poa pratensis c.t. 21
Populus tremuloides/Juniperus communis/Astragalus miser c.t. 21
Populus tremuloides/Veratrum californicum c.t. 22
Populus tremuloides/Heracleum lanatum c.t. 22
Populus tremuloides/Pteridium aquilinum c.t. 23
Populus tremuloides/Senecio serra c.t. 24
Populus tremuloides/Carex geyeri c.t. 26
Populus tremuloides/Festuca thurberi c.t. 27
Populus tremuloides/Sitanion hystrix c.t. 28
Populus tremuloides/Bromus carinatus c.t. 28
Populus tremuloides/Poa pratensis c.t. 29
Populus tremuloides-Abies lasiocarpa/Vaccinium caespitosum c.t. 30
Populus tremuloides-Abies lasiocarpa/Amelanchier alnifolia c.t. 31
Populus tremuloides-Abies lasiocarpa/Symphoricarpos oreophilus/Senecio serra c.t. 31
Populus tremuloides-Abies lasiocarpa/Symphoricarpos oreophilus/Carex geyeri c.t. 32
Populus tremuloides-Abies lasiocarpa/Juniperus communis c.t. 33
Populus tremuloides-Abies lasiocarpa/Senecio serra c.t. 33

Page

Populus tremuloides-Abies lasiocarpa/Carex geyeri c.t. 35
Populus tremuloides-Abies concolor/Symphoricarpos oreophilus c.t. 36
Populus tremuloides-Abies concolor/Juniperus communis c.t. 36
Populus tremuloides-Pseudotsuga menziesii/Amelanchier alnifolia c.t. 37
Populus tremuloides-Pseudotsuga menziesii/Juniperus communis c.t. 37
Populus tremuloides-Pinus ponderosa/Quercus gambelii c.t. 38
Populus tremuloides-Pinus ponderosa/Juniperus communis c.t. 38
Populus tremuloides-Pinus contorta/Vaccinium scoparium c.t. 39
Populus tremuloides-Pinus contorta/Juniperus communis c.t. 40
References 41
Appendix A: Constancy and Average Canopy Cover of Important Species by Aspen Community Types in Utah 42
Appendix B1: Means, Standard Errors (SE), and Ranges of Basal Area, Stand Age, Stand Height, and Site Index for *Populus tremuloides* by Community Types in Utah, in Metric Units 54
Appendix B2: Means, Standard Errors (SE), and Ranges of Basal Area, Stand Size, Stand Height, and Site Index for *Populus tremuloides* by Community Types in Utah, in English Units 56
Appendix C: Means, Standard Errors (SE), and Ranges of Tree Basal Area, and Percent of this Basal Area Consisting of Conifers, by Community Type in Utah 59
Appendix D1: Means, Standard Errors (SE), and Ranges of Annual Undergrowth Production by Vegetation Classes Expressed in Dry Weight Kilograms per Hectare 62
Appendix D2: Means, Standard Errors (SE), and Ranges of Annual Undergrowth Production by Vegetation Classes Expressed in Dry Weight Pounds per Acre 64
Appendix E: Proportion of Yearly Undergrowth Production in Different Vegetation Categories by Aspen Community Types, and the Suitability of this Undergrowth as Livestock Forage 67
Appendix F: Proportion of Aspen Stands Sampled in Each of Utah's National Forests that Were Classified in Different Aspen Community Types 68
Appendix G: Utah Aspen Community Type Field Form 69

Aspen Community Types of Utah

Walter F. Mueggler
Robert B. Campbell, Jr.

INTRODUCTION

Aspen (*Populus tremuloides* Michx.) forests are a classic example of multiple-use wildlands. Traditionally recognized for their importance as summer range for livestock, prime habitat for many species of wildlife, productive watersheds, and their scenic contribution, aspen forests in the West are rapidly gaining importance as well for their potential to produce wood fiber. In addition, aspen lands contribute greatly to vegetation diversity wherever they occur in the Intermountain and Rocky Mountain States.

Utah contains over 1.6 million acres (648 000 ha) of aspen-dominated forests (Green and Van Hooser 1983). These aspen forests span a broad range of environments and are of varied successional status. Aspen thrive under a variety of elevation, moisture, and soil conditions and are thus associated with widely diverse vegetation types. These range from the cool, moist, high-elevation spruce-fir forests, where aspen frequently plays a dominant successional role, to the relatively dry, low-elevation sagebrush steppes where permanent, isolated aspen groves are a highly valued part of the landscape.

Aspen lands are a prominent part of the vegetation complex on all six of Utah's National Forests, which encompass the high plateaus and mountain ranges of the State (fig. 1). These highlands form essentially a continuous chain through the center of Utah, from Idaho and Wyoming southward to the Arizona border.

Aspen generally occupies an intermediate elevation zone in these highlands, which gets progressively higher as latitude decreases. On the Wasatch-Cache National Forest in northern Utah (fig. 1), for example, aspen forests are commonly found between 5,900 and 9,200 ft (1 800 and 2 800 m) elevation. In southern Utah on the Dixie National Forest, aspen forests most frequently occur between 7,500 and 10,500 ft (2 300 and 3 200 m) elevation. Aspen is usually a seral tree in climax subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) associations at the higher elevations. In such situations it may dominate the forest community for many decades following severe disturbance, such as fire or clearcutting, but will gradually decline as the conifers become reestablished. At lower elevations aspen can occur either as a temporarily dominant seral species in a variety of climax conifer associations, or it can achieve permanent dominance as the climax forest type. The environmental conditions related to aspen's role as a seral and as a climax species remain ill-defined.

The variety of undergrowth on aspen lands, caused by the range of abiotic environments suitable for aspen growth and aspen's ability to function as a seral-dominant as well as a climax-dominant tree, is compounded by the general use of these lands for grazing. Aspen lands have provided prime summer range for both sheep and cattle in Utah since settlement in the latter half of the 19th century. Some 100 years of grazing at varying intensity (frequently very intense in the early 1900's), and by different classes of livestock, have left their mark in often severe alteration of undergrowth composition and production. Some of these alterations are pronounced; others are subtle and difficult to assess.

The broad environmental and successional diversity encompassed by Utah's aspen lands is reflected inevitably by variations in the forage, wildlife habitat, wood, and water to be derived from these lands. Additionally, equal variability can be expected in the response of these lands to management activities. Such diversity needs to be partitioned into manageable units to facilitate intensive resource management. This is usually done by classification. Since about 1970, considerable effort has been devoted to developing habitat type classifications for wildlands in the Western United States. Habitat types, as conceptualized and used by Daubenmire and Daubenmire (1968), are aggregations of land units capable of supporting similar climax plant communities and are based upon species composition of climax communities. These classifications are useful to resource managers for partitioning lands and as a basis for structuring management recommendations. Habitat type classifications have recently been developed for the coniferous forests of northern Utah (Mauk and Henderson 1984) and for southern Utah (Youngblood and Mauk 1985). In these classifications, aspen was primarily considered to be either a species seral to a conifer climax or else persistently seral with unknown climax potential. Consequently, the aspen type was described only superficially.

The widespread dominance of aspen on extensive portions of Utah's wildlands increased the need for a classification that would partition the variability of this important forest type. Ideally, the classification should incorporate information related to the successional as well as to the climax status of aspen. The habitat-type approach did not appear feasible for such a classification because of its reliance on potential rather than existing vegetation, and the uncertain successional status of aspen in different situations. Determining precisely the influence of widespread disturbance, whether natural or human-caused, results at best in tenuous projection of potential climax composition under the range of environments suited to aspen dominance. A community-type

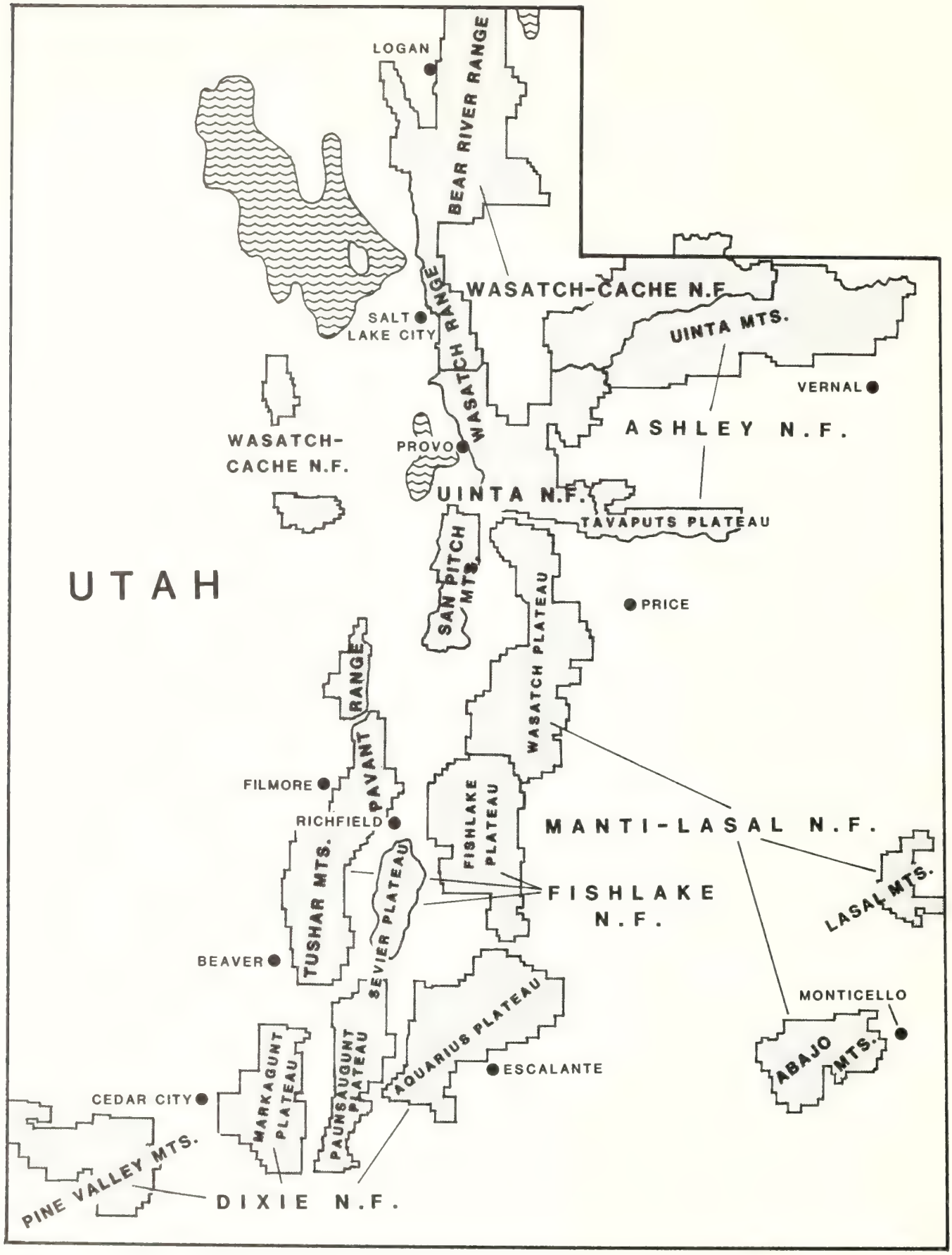


Figure 1.—National Forest lands in Utah covered by this classification and the location of the major mountain divisions discussed in the text.

approach is appropriate, however, because it avoids the presumption of climax.

Community types are aggregations of similar plant communities based upon existing floristics regardless of successional status. As with habitat types, community types view the plant community as an environmental integrator, and thus reflect major environmental differences. Community types may either represent climax plant associations or represent successional stages toward climax plant associations. In either event, resource managers in the field must contend with this existing vegetation. Once community types are defined, effort can be directed toward establishing successional relationships and linking seral community types to known habitat types where appropriate. Meanwhile, the community types can be used as a basis for mapping and resource management planning.

Community type classifications for aspen lands have been developed within the Forest Service's Intermountain Region for the Bridger-Teton National Forest in western Wyoming (Youngblood and Mueggler 1981) and for the Targhee and Caribou National Forests in southeastern Idaho (Mueggler and Campbell 1982). This classification extends the earlier efforts southward to describe aspen lands on and near the six National Forests in Utah: Wasatch-Cache, Uinta, Ashley, Manti-LaSal, Fishlake, and Dixie. During the process of structuring these aspen-land classifications for the Intermountain Region, concepts have continued to evolve that we hope will enhance their use. Our objective was to produce aspen-land classifications, and supporting information, that would serve to facilitate multiple-use management in the Intermountain Region.

METHODS

The community-type approach to classification development necessitates extensive sampling to adequately encompass and replicate the variation in composition of existing vegetation resulting from both abiotic and biotic environmental influences. However, acquisition of quantitative data on stand structure, undergrowth productivity, and certain other desired factors can be laborious. Because we did not have the resources to measure all stands at the desired intensity and still acquire an adequate number of stands upon which to base a useful classification, we used a dual sampling approach. One person sampled reconnaissance plots by traveling independently from a two-person crew responsible for sampling the separate and more time-consuming intensive plots. On the reconnaissance plots, species composition was estimated, and some environmental factors were characterized. The intensive plots yielded data on stand structure, age, productivity, and environment as well as species composition.

Field Methods

Aspen stands for sampling were found primarily by traveling forest roads throughout Utah looking for reasonably accessible candidates. We used only two selection criteria: at least 50 percent of the tree canopy cover had to consist of aspen, and the stand had to be large enough to contain a single macroplot within an apparently uniform environment. Our intent was to sample the full environmental range where aspen expressed dominance. Neither successional status nor grazing intensity were considerations in stand selection. Thus, although the actual selection of stands was subjective, this selection avoided preconceived bias that could influence the resulting classification.

Upon selection for intensive sampling, a single 1/13-acre (314-m^2) circular macroplot was established in a relatively uniform and representative portion of the stand. Ecotones at stand margins and atypical openings were avoided, as were clonal ecotones where a stand was composed of more than one discernible aspen clone. Tree data by species, collected from the entire macroplot, consisted of: an ocular estimate of overhead canopy cover; reproduction as number of stems with heights less than 4 inches (1 dc), 4 to 12 inches (1 to 3 dc), and 12 to 55 inches (3 to 14 dc); number of stems by 2-inch (5-cm) diameter at breast height (d.b.h.) size classes; and age, height, and d.b.h. of individual trees selected to represent the dominants and other well-defined size strata. We determined species composition of the undergrowth shrubs and herbs by estimating canopy cover by species, based upon careful overall scrutiny of the entire macroplot. In addition, we estimated canopy cover for the vegetational classes of shrubs, graminoids, forbs, and annuals. Undergrowth biomass was determined by a combination of estimating and clipping current year's growth of shrubs below 5 ft (1.5 m) high, and herbs on three sets of microplots randomly distributed on the 1/13-acre (314-m^2) macroplot. Each set of microplots consisted of a cluster of five circular 5.4-ft^2 (0.5-m^2) plots on which the current growth on four was estimated as a percentage of the fifth, which was then clipped. The clipped material was saved and later dried for 48 h at 158 °F (70 °C). The percentage estimates from the four plots in a set were then converted to dry weight. An estimated correction was applied at the time of sampling to adjust the weights for sampling either before or after the time of peak standing crop, as well as to compensate for obvious livestock use. These adjustments were highly subjective but deemed necessary to compensate for obvious production distortions caused by time of sampling and use. Estimated undergrowth production, therefore, was based on 15 microplots per stand. All production values given are dry weights. We determined the following environmental factors for each intensively sampled stand: elevation, aspect, percent slope, landform, soil parent material, depth of melanized layer, and estimates of rooting depth, soil rockiness, and soil texture. We also recorded location, evidence of succession, livestock use, and other interpretative information.

The considerably more rapid reconnaissance technique consisted of choosing an approximately 1/10-acre (1/25-ha) uniform portion of the stand to be sampled and estimating selected vegetation factors. Canopy cover of each tree species was estimated separately for that portion over 4.6 ft (1.4 m) high and the reproduction under this height. Percentage canopy cover for each shrub and herbaceous species, as well as for vegetation classes, was estimated after carefully scrutinizing the area. We

recorded the environmental factors of elevation, aspect, landform, and soil parent material, and also location and interpretative information related to succession and animal use.

Data from 1,233 aspen stands were accumulated in this manner to form the basis for describing the aspen communities in Utah. We sampled 421 of these stands intensively; the remaining 812 were sampled by the reconnaissance technique.

Data Analysis

Prior to placing the field data on computer file for analysis, we confirmed the identification of voucher plant specimens and identified the collections of questionable species. The coding and key-punching of all vegetation and environmental data were checked for errors.

Development of the classification categories relied principally upon use of synthesis or association tables (Mueller-Dombois and Ellenberg 1974). Before the process of stand alignment and reiteration began, every tenth stand was temporarily deleted from the file to serve as an unbiased validation of the classification that would be developed, and validation of the field key constructed to assist in identification of the community types. These validation stands were subsequently reintroduced into the data file for compilation of all tables summarizing the community type data. The synthesis table method permitted subjective recognition of similarities in vegetation structure and in species fidelity, constancy, and coverage. We considered certain species to be indicative of natural succession, environment, grazing degradation, and management concerns; numerous reiterations of stand alignments permitted sequencing according to visual similarities of these important species.

We subsequently grouped the stands into community types according to the constancy and abundance of the selected indicator species. Similarity of vegetational structure was a prime consideration in forming the groups. The presence or absence of substantial amounts of conifers in the overstory, or potentially so as judged by conifer regeneration, was the first separation criterion. These were categorized as aspen-conifer cover types (table 1). The presence of substantial amounts of conifers was considered highly relevant because of successional implications. In the normal course of succession, all such mixed cover types will probably succeed to coniferous forest climax communities. The presence of a tall shrub layer and of a low shrub layer were the second and third criteria considered in grouping stands. These shrub layers not only tend to reflect environmental differences but are also highly relevant to management.

We selected the indicator species in the herbaceous layer as the most sensitive indicators of abiotic environmental extremes and of severe vegetational alterations caused by prolonged excessive grazing. Thus, species' prevalence within the tree, shrub, and herb life-form classes were used to delineate and characterize the aspen community types.

After we grouped the stands into what appeared to be sensible community types, we prepared a dichotomous key based upon characterizing species and checked against all stands used to develop the classification. This key was developed to facilitate field use of the classification. The last step was to use the key to classify the validation stands into community types and then to compare the species composition of these groups with that of the original groups used to develop the classification. Less than 5 percent of the original stands used to form the classification could not readily be placed into identifiable community types. Similarly, about 3 percent of the validation stands did not fit the classification. These undetermined stands (20 intensively sampled and 34 reconnaissance) are likely either unusual isolated communities, or else represent ill-defined community types reflecting restricted environmental situations.

Whether a community is seral or stable can appreciably affect management decisions. Therefore, the ability to judge the successional status of the aspen community types is important. Community stability is indicated when existing individuals are replaced by their own progeny, without disturbance; thus, the community is self-perpetuating. In seral communities, current populations of some species tend to be replaced by other species, resulting in gradual changes in composition. Although accurate determination of community stability may require intensive ecological study, preliminary determinations are possible by comparing vegetational composition with that of communities of known stability, evaluating the age structure of the woody species and the proportions of shade-tolerant species, and examining the relative abundance of species known to increase with such disturbance as excessive livestock grazing. We have attempted to clarify the successional status of the aspen community types in Utah by linking them to either Mauk and Henderson's (1984) coniferous forest habitat type classification for northern Utah, or to Youngblood and Mauk's (1985) classification for central and southern Utah, and to other community types in our aspen classification. At best, the linkages are only suggestive and will require intensive separate study for confirmation of the successional relationships. Our judgments of the successional status of each community type are shown in table 2.

Table 1.—Aspen community types (c.t.) by cover type categories in Utah

Cover type and community type	Abbreviation
Populus tremuloides cover type	
(Tall shrub undergrowth type)	
P. tremuloides/Acer grandidentatum/Pteridium aquilinum c.t.	POTR/ACGR/PTAQ
P. tremuloides/Prunus virginiana/Senecio serra c.t.	POTR/PRVI/SESE
P. tremuloides/Prunus virginiana/Carex geyeri c.t.	POTR/PRVI/CAGE
(Low shrub undergrowth type)	
P. tremuloides/Sambucus racemosa c.t.	POTR/SARA
P. tremuloides/Symphoricarpos oreophilus/Senecio serra c.t.	POTR/SYOR/SESE
P. tremuloides/Symphoricarpos oreophilus/Carex geyeri c.t.	POTR/SYOR/CAGE
P. tremuloides/Symphoricarpos oreophilus/Festuca thurberi c.t.	POTR/SYOR/FETH
P. tremuloides/Juniperus communis/Carex geyeri c.t.	POTR/JUCO/CAGE
P. tremuloides/Juniperus communis/Sitanion hystrix c.t.	POTR/JUCO/SIHY
P. tremuloides/Symphoricarpos oreophilus/Bromus carinatus c.t.	POTR/SYOR/BRCA
P. tremuloides/Symphoricarpos oreophilus/Poa pratensis c.t.	POTR/SYOR/POPR
P. tremuloides/Juniperus communis/Astragalus miser c.t.	POTR/JUCO/ASMI
(Herb undergrowth type)	
P. tremuloides/Veratrum californicum c.t.	POTR/VECA
P. tremuloides/Heracleum lanatum c.t.	POTR/HELA
P. tremuloides/Pteridium aquilinum c.t.	POTR/PTAQ
P. tremuloides/Senecio serra c.t.	POTR/SESE
P. tremuloides/Carex geyeri c.t.	POTR/CAGE
P. tremuloides/Festuca thurberi c.t.	POTR/FETH
P. tremuloides/Sitanion hystrix c.t.	POTR/SIHY
P. tremuloides/Bromus carinatus c.t.	POTR/BRCA
P. tremuloides/Poa pratensis c.t.	POTR/POPR
Populus tremuloides-Abies lasiocarpa cover type	
P. tremuloides-A. lasiocarpa/Vaccinium caespitosum c.t.	POTR-ABLA/VACA
P. tremuloides-A. lasiocarpa/Amelanchier alnifolia c.t.	POTR-ABLA/AMAL
P. tremuloides-A. lasiocarpa/Symphoricarpos oreophilus/ Senecio serra c.t.	POTR-ABLA/SYOR/SESE
P. tremuloides-A. lasiocarpa/Symphoricarpos oreophilus/ Carex geyeri c.t.	POTR-ABLA/SYOR/CAGE
P. tremuloides-A. lasiocarpa/Juniperus communis c.t.	POTR-ABLA/JUCO
P. tremuloides-A. lasiocarpa/Senecio serra c.t.	POTR-ABLA/SESE
P. tremuloides-A. lasiocarpa/Carex geyeri c.t.	POTR-ABLA/CAGE
Populus tremuloides-Abies concolor cover type	
P. tremuloides-A. concolor/Symphoricarpos oreophilus c.t.	POTR-ABCO/SYOR
P. tremuloides-A. concolor/Juniperus communis c.t.	POTR-ABCO/JUCO
Populus tremuloides-Pseudotsuga menziesii cover type	
P. tremuloides-P. menziesii/Amelanchier alnifolia c.t.	POTR-PSME/AMAL
P. tremuloides-P. menziesii/Juniperus communis c.t.	POTR-PSME/JUCO
Populus tremuloides-Pinus ponderosa cover type	
P. tremuloides-P. ponderosa/Quercus gambelii c.t.	POTR-PIPO/QUGA
P. tremuloides-P. ponderosa/Juniperus communis c.t.	POTR-PIPO/JUCO
Populus tremuloides-Pinus contorta cover type	
P. tremuloides-P. contorta/Vaccinium scoparium c.t.	POTR-PICO/VASC
P. tremuloides-P. contorta/Juniperus communis c.t.	POTR-PICO/JUCO

Table 2.—Apparent successional relationships between aspen community types (c.t.) in Utah and climax community types (c.c.t.), or previously described habitat types (h.t.). Type names enclosed in parentheses are less likely related than those not enclosed

Aspen community type		Climax community types or habitat types
POTR/ACGR/PTAQ	→	POTR/ACGR/PTAQ c.c.t. (POTR/PRVI/SESE c.c.t.)
POTR/PRVI/SESE	→	POTR/PRVI/SESE c.c.t. (ABLA/OSCH h.t.)[1]
POTR/PRVI/CAGE	→	POTR/PRVI/CAGE c.c.t. (ABLA/BERE h.t.)[1] (ABLA/CAGE h.t.)[2]
POTR/SARA	→	POTR/SARA c.c.t.
POTR/SYOR/SESE	→	POTR/SYOR/SESE c.c.t. (ABLA/OSCH h.t.)[1] (ABLA/ACCO h.t.)[2]
POTR/SYOR/CAGE	→	POTR/SYOR/CAGE c.c.t. (PSME/SYOR h.t.)[1,2] (PSME/BERE h.t.)[1,2] (ABLA/BERE h.t.)[1,2]
POTR/SYOR/FETH	→	POTR/SYOR/FETH c.c.t.
POTR/JUCO/CAGE	→	POTR/JUCO/CAGE c.c.t. (ABLA/JUCO h.t.)[1,2] (ABLA/BERE h.t.)[1,2] (PSME/BERE h.t.)[1,2]
POTR/JUCO/SIHY	→	POTR/JUCO/SIHY c.c.t. (PIPO/FEID h.t.)[1] (PSME/BERE h.t.)[2]
POTR/SYOR/BRCA	→	POTR/SYOR/SESE c.c.t. (ABLA/OSCH h.t.)[1] (ABLA/ACCO h.t.)[2]
POTR/SYOR/POPR	→	POTR/SYOR/CAGE c.c.t. POTR/SYOR/SESE c.c.t.
POTR/JUCO/ASMI	→	POTR/JUCO/CAGE c.c.t. (ABLA/JUCO h.t.)[1] (ABLA/BERE h.t.)[1]
POTR/VECA	→	POTR/VECA c.c.t.
POTR/HELA	→	POTR/HELA c.c.t.
POTR/PTAQ	→	POTR/PTAQ c.c.t. (POTR/SESE c.c.t.)
POTR/SESE	→	POTR/SESE c.c.t. (ABLA/OSCH h.t.)[1]
POTR/CAGE	→	POTR/CAGE c.c.t. (ABLA/BERE h.t.)[1,2]

Table 2. (Con.)

Aspen community type		Climax community types or habitat types
POTR/FETH	→	POTR/FETH c.c.t. (POTR/SYOR/FETH c.c.t.)
POTR/SIHY	→	POTR/SIHY c.c.t. (PIPO/FEID h.t.)[1] (PIPO/SYOR h.t.)[2]
POTR/BRCA	→	POTR/SESE c.c.t. (POTR/SYOR/SESE c.c.t.) (ABLA/OSCH h.t.)[1]
POTR/POPR	→	POTR/CAGE c.c.t. POTR/SYOR/CAGE c.c.t. (ABLA/BERE h.t.)[1,2]
POTR-ABLA/VACA	→	ABLA/VACA h.t.[1] (ABLA/VASC h.t.)[1]
POTR-ABLA/AMAL	→	ABLA/OSCH h.t.[1] ABLA/ACGL h.t.[1]
POTR-ABLA/SYOR/SESE	→	ABLA/OSCH h.t.[1]
POTR-ABLA/SYOR/CAGE	→	ABLA/CAGE h.t.[2] ABLA/BERE h.t.[1,2]
POTR-ABLA/JUCO	→	ABLA/JUCO h.t.[1,2] ABLA/BERE h.t.[1,2]
POTR-ABLA/SESE	→	ABLA/OSCH h.t.[1] (ABLA/ACCO h.t.)[2]
POTR-ABLA/CAGE	→	ABLA/CARO h.t.[2]
POTR-ABCO/SYOR	→	ABCO/BERE h.t.[1,2] (ABCO/OSCH h.t.)[1]
POTR-ABCO/JUCO	→	ABCO/JUCO h.t.[2] (PIPU/JUCO h.t.)[2]
POTR-PSME/AMAL	→	PSME/OSCH h.t.[1] PSME/ACGL h.t.[1] PSME/BERE h.t.[1]
POTR-PSME/JUCO	→	PSME/BERE h.t.[1,2] PSME/SYOR h.t.[1,2]
POTR-PIPO/QUGA	→	PIPO/CAGE h.t.[1] PIPO/QUGA h.t.[2] (PIPO/SYOR h.t.)[2]
POTR-PIPO/JUCO	→	PIPO/FEID h.t.[1] PIPO/SYOR h.t.[2]
POTR-PICO/VASC	→	PICO/VASC h.t.[1] ABLA/VASC h.t.[1]
POTR-PICO/JUCO	→	PICO/BERE h.t.[1] ABLA/BERE h.t.[1] ABLA/JUCO h.t.[1]

[1]Described by Mauk and Henderson (1984).
[2]Described by Youngblood and Mauk (1985).

An objective index to probable successional relationship between the community types in the aspen-conifer cover type series and recognized conifer habitat types (Mauk and Henderson 1984; Youngblood and Mauk 1985) was arrived at by computing a similarity index comparing species' presence. Our premise was that species with high constancy in one type are more likely to occur with higher constancy in a related than in a nonrelated type. A constancy of 50 percent in either one of the compared types was required for a species to be included in the comparison. Sorensen's community coefficient (Mueller-Dombois and Ellenberg 1974) was then computed as an objective similarity index comparing the similarity of species constancy values for the two types.

Data on 460 plant species representing 210 genera were collected and evaluated. Of these, we used 168 of the more important species to prepare the tables in appendix A, which summarize the constancy of occurrence of species within community types and their average canopy cover. These tables permit a ready comparison of species composition in the different aspen community types.

The basal area and site index of aspen are summarized by community type in appendix B. We computed 80-year site index for each of the intensively sampled stands using Jones' (1967) site index curves for aspen. Appendix C contains total tree basal area and the percent consisting of conifers.

Undergrowth production, composition by vegetational classes, and forage suitability are summarized in appendixes D and E. We derived an approximation of suitability as livestock forage from species forage suitability ratings developed for the Intermountain Region by USDA Forest Service (1981), and then adjusted this to a percentage composition based on canopy cover estimates. We consider the proportion of canopy cover composed of species in each of three suitability classes (desirable, intermediate, least) to be an index to the value of the undergrowth as livestock forage. This was computed for each community type by summing the constancy times the cover data (appendix A) for each species within each suitability class, and dividing by the summation of constancy times cover for all classes to give a relative percentage within each class.

Appendix F shows the proportion of the stands sampled on each of Utah's six National Forests that were in each community type. A field form (appendix G) is provided to facilitate acquisition of the data needed to classify Utah aspen lands.

Other Considerations

An understanding of the general concepts guiding development of this classification may add perspective to its potential use. We sought to develop a natural classification, yet one that would incorporate technical considerations, particularly with respect to vegetational structure and type nomenclature. Perceived usefulness was an overriding consideration. Vegetation structure is considered important because of its effect on undergrowth composition and production, its reflection of environment, and its possible relevancy to management. The nomenclature of the community types is arranged to reflect up to three distinct structural layers that commonly form aspen communities: the overstory tree layer, the shrub layer (when present), and the herbaceous layer. The type name consists of the name of the indicator species within each layer separated by a slash.

The classification is based upon existing rather than potential vegetation. Thus, the units should be readily recognizable by forest and range technicians. However, because it is a classification of existing vegetation, the units reflect the effects of both abiotic and biotic influences. This problem is abated somewhat by our attempt to indicate the probable successional status of each type and its relationship to recognized habitat types. In arriving at type separations, our approach was to stress the "boundary" or difference between types rather than the modal conditions of each type. Usually we found it best to separate the wettest types first and proceed to those occupying drier sites. Our concept was that species with high moisture requirements have more difficulty growing under drier conditions than species with less stringent moisture requirements have in growing under wetter conditions.

A word of explanation regarding our concept of plant community organization. Seldom, if ever, do plant communities fall into clearcut taxonomic units, because no two plant communities are identical; species composition differs from place to place because of environmental and successional gradients and because of chance. Even where environmental stability and lack of physical disturbance have permitted the development of climax communities, subtle differences in the microenvironment, and the factor of chance, contribute to certain differences in the kinds and amounts of species making up each community. Such differences in species composition are even more pronounced in seral vegetation, which reflects, in addition, the variable effects of past disturbance. Vegetation classification, therefore, becomes a matter of arbitrarily deciding upon the amount of variability in composition tolerable in defining the taxonomic units. The amount of variability acceptable should be determined by the need for and projected use of the resulting classification.

No single flora satisfactorily described all plant species encountered during the course of our study. We relied heavily on Hitchcock and Cronquist (1973) for northern Utah, and Harrington (1954) for general Utah coverage. Welsh and Moore (1973), Martin and Hutchins (1980), and Arnow and others (1977) were used to help clarify identifications when the primary floras appeared inadequate.

Certain species nomenclature usage should be noted. The difficulty of separating some species without flowers or mature fruits was resolved by combining the species in question. Thus, *Osmorhiza chilensis* and *Osmorhiza depauperata* are treated as *O. chilensis,* and *Rosa woodsii* and *Rosa nutkana* are under *R. woodsii.* Other species, though separately identified in the field, were combined in the community-type summaries for convenience because of their similarity. These are: *Sambucus racemosa* and *Sambucus cerulea* as *S. racemosa; Fragaria vesca* and *Fragaria virginiana* as

F. vesca; Polemonium foliosissimum and *Polemonium occidentale* as *P. foliosissimum;* and *Delphinium occidentale* and *Delphinium barbeyi* as *D. occidentale.* Nomenclature ambiguities forced a somewhat arbitrary selection of names for some species. Thus the *Agropyron trachycaulum-Agropyron subsecundum-Agropyron caninum* complex is treated as *A. trachycaulum; Bromus marginatus* and *Bromus polyanthus* are included with *Bromus carinatus;* and *Stipa columbiana* and *Stipa nelsonii* are lumped with *Stipa occidentalis.* The traditional name of *Koeleria cristata* is used to include *Koeleria nitida.* Considerable confusion revolves around the separation of *Geranium viscosissimum* and *Geranium fremontii.* This confusion is reflected by different floras in adjacent States that seldom treat both species and that may indicate that *G. fremontii* is synonymous with *G. viscosissimum.* We have arbitrarily chosen to call this uncertain, pink-flowered complex *G. viscosissimum.*

THE CLASSIFICATION: VEGETATION KEY

This classification partitions those forests in Utah where aspen comprises at least 50 percent of the tree canopy into six cover types based upon the dominant and codominant trees. These cover types are then separated into 36 community types based upon prominent indicator species in the undergrowth. Table 3 is the vegetation key for the classification.

Although aspen generally has relatively broad environmental tolerances, it typically is less shade tolerant and shorter lived than most conifers. Thus, aspen stands that contain a substantial element of conifers are considered to be at a seral stage leading toward a conifer climax. They are categorized as aspen-conifer cover types. The aspen-conifer cover types are separated by minimal amounts of conifer occurrence, giving sequential consideration first to those conifers that require the less stressful moist sites, and proceeding eventually to those that are able to occupy the driest sites. *Pinus contorta,* an exception, is taken out last because it is usually considered seral to other conifers. At least 5 percent canopy cover of *Abies lasiocarpa,* alone or combined with *Picea engelmannii,* qualifies a stand for the *Populus tremuloides-Abies lasiocarpa* cover type. At least 10 percent canopy cover is required for *Abies concolor, Pseudotsuga menziesii,* and *Pinus contorta*; only 5 percent is required for *Pinus ponderosa.* These minimal cover requirements are subjectively judged to be more than accidental and to approximate the level required for the conifer species to validly indicate site differences, as well as being indicative of successional trends.

The *Populus tremuloides* cover type is further subdivided into three undergrowth types based upon vegetational structure. Those communities possessing a distinct tall shrub component are placed in the tall shrub undergrowth type. Those without a tall shrub layer but that possess a distinct layer of low shrubs are placed in the low shrub undergrowth type. Community types that lack a well-defined layer of shrubs are placed within the herb undergrowth type.

The largest number of community types (21) occurred within the *Populus tremuloides* cover type. The *P. tremuloides-A. lasiocarpa* cover type contained seven community types; the remaining four cover types contained only two community types each. Community types were based on as few as two stands in one case where composition and environment were unique (and the type had been reported elsewhere), to as many as 152 stands in the most common type. Over 40 percent of the stands classified fell into only four community types: *P. tremuloides/Symphoricarpos oreophilus/Senecio serra* c.t.; *P. tremuloides/S. serra* c.t.; *P. tremuloides/Prunus virginiana/S. serra* c.t.; and *P. tremuloides-A. lasiocarpa/S. serra* c.t. Over half of the community types were infrequent but are considered valid because of their repeated occurrence in the large number of stands that served as our data base. A listing of all community types is given in table 1. Less than 5 percent of all stands sampled could not be matched with any of the 36 community types listed.

Table 3.—Vegetation key to aspen community types (c.t.) in Utah, where *Populus tremuloides* constitutes at least 50 percent of the tree canopy

Note: The "tall forb group" referred to in this key consists of the following species:

Agastache urticifolia	*Polemonium foliosissimum*
Aster engelmannii	*Rudbeckia occidentalis*
Delphinium occidentale	*Scrophularia lanceolata*
Mertensia arizonica	*Senecio serra*
Osmorhiza occidentalis	*Valeriana occidentalis*

Note: Adjective descriptors:
trace = less than 1% cover
scarce, present, readily apparent = 1% to 4% cover
conspicuous = 5% or greater cover
prominent = 10% or greater cover

Key to cover types:

I. *Abies lasiocarpa* and/or *Picea engelmannii* at least 5% canopy cover ..... *Populus tremuloides-Abies lasiocarpa* (Go to B)

I. *A. lasiocarpa* and/or *P. engelmannii* less than 5% cover II

II. *Abies concolor* and/or *Picea pungens* at least 10% canopy cover ..... *Populus tremuloides-Abies concolor* (Go to C)

II. *A. concolor* and/or *P. pungens* less than 10% cover III

III. *Pseudotsuga menziesii* at least 10% canopy cover ..... *Populus tremuloides-Pseudotsuga menziesii* (Go to D)

III. *P. menziesii* less than 10% cover IV

IV. *Pinus ponderosa* at least 5% canopy cover ..... *Populus tremuloides-Pinus ponderosa* (Go to E)

IV. *P. ponderosa* less than 5% cover V

V. *Pinus contorta* at least 10% canopy cover ..... *Populus tremuloides-Pinus contorta* (Go to F)

V. *P. contorta* less than 10% cover VI

VI. Some other coniferous trees at least 10% canopy cover ..... Unclassified cover type

VI. Not as above ..... *Populus tremuloides* (Go to A)

Key to community types:

A. (*Populus tremuloides* cover type)

1. *Prunus virginiana, Amelanchier alnifolia,* or *Acer grandidentatum* (alone or in combination) prominent, generally exceeding 10% canopy cover ..... Tall shrub group (Go to AA)

1. Above-named shrubs totaling less than 10% cover 2

2. *Symphoricaropos oreophilus* prominent with at least 10% canopy cover, or *Juniperus communis* and/or *Artemisia tridentata* conspicuous with at least 5% combined cover, or *Sambucus racemosa* and/or *Sambucus cerulea* with at least 5% cover ..... Low shrub group (Go to AB)

2. Not as above ..... Herb group (Go to AC)

AA. (Tall shrub undergrowth type)

1. *Pteridium aquilinum* conspicuous with at least 5% cover: usually dominates herbaceous layer ..... *Populus tremuloides/Acer grandidentatum/Pteridium aquilinum* c.t. (p. 13)

1. *P. aquilinum* absent, or present in only trace amounts 2

2. One or more members of the tall forb group readily apparent, or *Bromus carinatus* and/or *Elymus glaucus,* alone or in combination usually forming a conspicuous part of herbaceous layer ..... *Populus tremuloides/Prunus virginiana/Senecio serra* c.t. (p. 14)

2. Neither tall forbs nor *B. carinatus* or *E. glaucus* conspicuous 3

3. *Carex geyeri, Carex rossii,* and/or *Stipa occidentalis* conspicuous ..... *Populus tremuloides/Prunus virginiana/Carex geyeri* c.t. (p. 15)

3. Not as above ..... Unclassified type

(con.)

Table 3. (Con.)

AB. (Low shrub undergrowth type)

1.	*Sambucus racemosa* and/or *Sambucus cerulea* conspicuous with at least 5% canopy cover	*Populus tremuloides/Sambucus racemosa* c.t. (p. 15)
1.	*S. racemosa* and *S. cerulea* usually absent; if present, then less than 5% cover	2
2.	*Juniperus communis* generally exceeding 5% canopy cover	3
2.	*J. communis* absent or scarce, less than 5% cover	8
3.	*Festuca thurberi* conspicuous with at least 5% cover; *Symphoricarpos oreophilus* usually present	*Populus tremuloides/Symphoricarpos oreophilus/Festuca thurberi* c.t. (p. 18)
3.	*F. thurberi* usually absent; if present, less than 5% canopy cover	4
4.	*Carex geyeri, Carex rossii,* or *Stipa occidentalis* (alone or in combination) conspicuous, usually with at least 5% canopy cover	*Populus tremuloides/Juniperus communis/Carex geyeri* c.t. (p. 18)
4.	Not as above	5
5.	*Sitanion hystrix, Stipa comata,* and *Stipa lettermanii* (alone or in combination) conspicuous, usually at least 5% total canopy cover	*Populus tremuloides/Juniperus communis/Sitanion hystrix* c.t. (p. 20)
5.	Not as above	6
6.	*Astragalus miser* prominent with at least 10% canopy cover	*Populus tremuloides/Juniperus communis/Astragalus miser* c.t. (p. 21)
6.	*A. miser* absent, or forming only an incidental part of the herbaceous layer	7
7.	*Poa pratensis* and *Symphoricarpos oreophilus* prominent, each with at least 10% cover	*Populus tremuloides/Symphoricarpos oreophilus/Poa pratensis* c.t. (p. 21)
7.	Not as above	Unclassified type
8.	*Symphoricarpos oreophilus* prominent, at least 10% canopy cover	13
8.	*S. oreophilus* absent or scarce, less than 10% cover	9
9.	*Artemisia tridentata* present with at least 5% cover	10
9.	*A. tridentata* absent or scarce	Go to AC
10.	*Carex geyeri, Carex rossii,* and/or *Stipa occidentalis* (alone or in combination) conspicious with at least 5% canopy cover	*Populus tremuloides/Juniperus communis/Carex geyeri* c.t. (p. 18)
10.	Not as above	11
11.	*Sitanion hystrix, Stipa comata,* and/or *Stipa lettermanii* (alone or in combination) conspicuous usually with at least 5% canopy cover	*Populus tremuloides/Juniperus communis/Sitanion hystrix* c.t. (p. 20)
11.	Above-named grasses absent or present only in trace amounts	12
12.	*Astragalus miser* abundant, usually with at least 10% cover	*Populus tremuloides/Juniperus communis/Astragalus miser* c.t. (p. 21)
12.	*A. miser* absent, or comprising only an incidental part of the herbaceous layer	Unclassified type
13.	*Festuca thurberi* conspicuous with at least 5% canopy cover	*Populus tremuloides/Symphoricarpos oreophilus/Festuca thurberi* c.t. (p. 18)
13.	*F. thurberi* generally absent; if present, less than 5% canopy cover	14
14.	One or more members of the tall forb group readily apparent, alone or in combination usually forming a conspicuous part of the herbaceous layer	*Populus tremuloides/Symphoricarpos oreophilus/Senecio serra* c.t. (p. 16)
14.	Members of the tall forb group absent or in total occur in only trace amounts	15

(con.)

Table 3. (Con.)

15.	*Carex geyeri, Carex rossii,* and *Stipa occidentalis* (alone or in combination) conspicuous with at least 5% canopy cover	*Populus tremuloides/Symphoricarpos oreophilus/Carex geyeri* c.t. (p. 17)
15.	Not as above	16
16.	*Sitanion hystrix, Stipa comata,* and *Stipa lettermanii* (alone or in combination) conspicuous with at least 5% canopy cover	*Populus tremuloides/Juniperus communis/Sitanion hystrix* c.t. (p. 20)
16.	Above grasses usually absent; less than 5% cover if present	17
17.	*Bromus carinatus* and/or *Elymus glaucus* a conspicuous part of the herbaceous layer, usually with more than 5% cover	*Populus tremuloides/Symphoricarpos oreophilus/Bromus carinatus* c.t. (p. 20)
17.	*B. carinatus* and *E. glaucus* absent or scarce	18
18.	*Poa pratensis* and *Taraxacum officinale* among the most prominent perennials in the herbaceous layer	*Populus tremuloides/Symphoricarpos oreophilus/Poa pratensis* c.t. (p. 21)
18.	Not as above	Unclassified type

AC. (Herb undergrowth type)

1.	*Veratrum californicum* prominent, generally exceeding 5% canopy cover	*Populus tremuloides/Veratrum californicum* c.t. (p. 22)
1.	*V. californicum* generally absent; if present, less than 5% canopy cover	2
2.	*Pteridium aquilinum* usually abundant, with at least 10% canopy cover	*Populus tremuloides/Pteridium aquilinum* c.t. (p. 23)
2.	*P. aquilinum* usually absent; if present, then less than 10% cover	3
3.	*Heracleum lanatum* a conspicuous part of the herbaceous layer with usually more than 5% canopy cover	*Populus tremuloides/Heracleum lanatum* c.t. (p. 22)
3.	*H. lanatum* absent or present in only trace amounts	4
4.	One or more members of the tall forb group readily apparent, alone or in combination forming a conspicuous part of the herbaceous layer	*Populus tremuloides/Senecio serra* c.t. (p. 24)
4.	Members of the tall forb group either absent or in total occur in trace amounts	5
5.	*Festuca thurberi* present with at least 2% canopy cover	*Populus tremuloides/Festuca thurberi* c.t. (p. 27)
5.	*F. thurberi* usually absent; if present, then less than 2% cover	6
6.	*Sitanion hystrix* and/or *Stipa comata* conspicuous with at least 5% canopy cover	*Populus tremuloides/Sitanion hystrix* c.t. (p. 28)
6.	*S. hystrix* and *S. comata* usually absent; if present, less than 5% cover	7
7.	*Carex geyeri, Carex rosii, Carex obtusata, Stipa occidentalis,* or *Calamagrostis rubescens* (alone or in combination) conspicuous with at least 5% cover; *Astragalus miser* often abundant.	*Populus tremuloides/Carex geyeri* c.t. (p. 26)
7.	Not as above	8
8.	*Bromus carinatus* and/or *Elymus glaucus* abundant, usually with at least 10% canopy cover	*Populus tremuloides/Bromus carinatus* c.t. (p. 28)
8.	Not as above	9
9.	*Poa pratensis* and/or *Taraxacum officinale* among the most prominent perennials in the herbaceous layer	*Populus tremuloides/Poa pratensis* c.t. (p. 29)
9.	Not as above	Unclassified type

B. (*Populus tremuloides-Abies lasiocarpa* cover type)

1.	*Amelanchier alnifolia, Prunus virginiana,* or *Acer grandidentatum* prominent, alone or in combination usually having at least 10% canopy cover; members of the tall forb group usually present	*Populus tremuloides-Abies lasiocarpa/Amelanchier alnifolia* c.t. (p. 31)
1.	Not as above	2
2.	*Vaccinium caespitosum* or *Vaccinium scoparium* abundant, usually well over 10% cover	*Populus tremuloides-Abies lasiocarpa/ Vaccinium caespitosum* c.t. (p. 30)

(con.)

Table 3. (Con.)

	2.	*V. caespitosum* and *V. scoparium* generally absent; if present, they occur only as incidental species	3
	3.	*Juniperus communis* conspicuous, generally with at least 5% canopy cover	*Populus tremuloides-Abies lasiocarpa/Juniperus communis* c.t. (p. 33)
	3.	*J. communis* absent or occurring in only trace amounts	4
	4.	*Symphoricarpos oreophilus* usually prominent, at least 10% cover; if scarce or absent, then *Rubus parviflorus* present in greater than trace amounts	7
	4.	Not as above	5
	5.	One or more members of the tall forb group, or *Bromus carinatus* and/or *Elymus glaucus*, a conspicuous part of the herbaceous layer	*Populus tremuloides-Abies lasiocarpa/Senecio serra* c.t. (p. 33)
	5.	Not as above; these species either absent or occur only incidentally	6
	6.	*Carex geyeri, Carex rossii, Carex obtusata, Stipa occidentalis,* or *Astragalus miser* (alone or in combination) conspicuous, usually with at least 5% canopy cover	*Populus tremuloides-Abies lasiocarpa/Carex geyeri* c.t. (p. 35)
	6.	Not as above	Unclassified type
	7.	One or more members of the tall forb group, or *Bromus carinatus* and/or *Elymus glaucus*, a conspicuous part of the herbaceous layer	*Populus tremuloides-Abies lasiocarpa/ Symphoricarpos oreophilus/Senecio serra* c.t. (p. 31)
	7.	Not as above	8
	8.	*Carex geyeri, Carex rossii, Stipa occidentalis,* or *Astragalus miser* (alone or in combination) conspicuous, usually with at least 5% canopy cover	*Populus tremuloides-Abies lasiocarpa/ Symphoricarpos oreophilus/Carex geyeri* c.t. (p. 32)
	8.	Not as above	Unclassified type
C.	(*Populus tremuloides-Abies concolor* cover type)		
	1.	Both *Symphoricarpos oreophilus* conspicuous (at least 5% cover), and one or more members of the tall forb group or *Bromus carinatus* and/or *Elymus glaucus* a conspicuous part of the herbaceous layer	*Populus tremuloides-Abies concolor/ Symphoricarpos oreophilus* c.t. (p. 36)
	1.	Not as above	2
	2.	*Juniperus communis* present; members of the tall forb group, *Bromus carinatus,* and *Elymus glaucus* absent or merely incidental	*Populus tremuloides-Abies concolor/Juniperus communis* c.t. (p. 36)
	2.	Not as above	Unclassified type
D.	(*Populus tremuloides-Pseudotsuga menziesii* cover type)		
	1.	*Amelanchier alnifolia, Prunus virginiana,* or *Acer grandidentatum* (alone or in combination) present and usually abundant; *Juniperus communis* absent	*Populus tremuloides-Pseudotsuga menziesii/ Amelanchier alnifolia* c.t. (p. 37)
	1.	Not as above	2
	2.	*Juniperus communis* present and usually abundant	*Populus tremuloides-Pseudotsuga menziesii/ Juniperus communis* c.t. (p. 37)
	2.	*J. communis* absent	Unclassified type
E.	(*Populus tremuloides-Pinus ponderosa* cover type)		
	1.	*Quercus gambelii, Prunus virginiana,* or *Acer grandidentatum* (alone or in combination) abundant, usually exceeding 10% canopy cover	*Populus tremuloides-Pinus ponderosa/Quercus gambelii* c.t. (p. 38)
	1.	Above shrubs absent, or present in only incidental amounts	2
	2.	*Juniperus communis* present, usually accompanied by *Sitanion hystrix, Stipa comata,* or *Carex rossii*	*Populus tremuloides-Pinus ponderosa/Juniperus communis* c.t. (p. 38)

(con.)

Table 3. (Con.)

	2. Not as above	Unclassified type
F.	(*Populus tremuloides-Pinus contorta* cover type)	
	1. *Vaccinium scoparium* or *Vaccinium caespitosum* abundant, usually exceeding 10% canopy cover	*Populus tremuloides-Pinus contorta/Vaccinium scoparium* c.t. (p. 39)
	1. *V. scoparium* and *V. caespitosum* absent, or present in only trace amounts	2
	2. *Juniperus communis* present, usually accompanied by either *Carex geyeri, Carex rossii, Carex obtusata, Stipa occidentalis,* or *Festuca idahoensis*	*Populus tremuloides-Pinus contorta/Juniperus communis* c.t. (p. 40)
	2. Not as above	Unclassified type

TYPE DESCRIPTIONS

Populus tremuloides/Acer grandidentatum/Pteridium aquilinum Community Type (POTR/ACGR/PTAQ c.t.)

This minor community type was identified on the basis of 11 stands primarily along the Wasatch Range in northern Utah. A single example was encountered in the Uinta Mountains just northwest of Vernal and another in the Pine Valley Mountains in southwestern Utah. The Uinta stand lacked *Acer grandidentatum* but possessed a tall shrub layer dominated by *Amelanchier alnifolia.* The type appeared to favor northerly and easterly exposures at the lower elevations between 5,800 and 7,500 ft (1 770 and 2 290 m). It was usually found on soils derived from sandstones and at the lower toe-slope topographic positions.

The vegetation of this type is characterized by the virtual absence of conifers, a distinct tall shrub layer, and dominance of the herbaceous layer by *Pteridium aquilinum.* Occasional *Abies concolor* or *Abies lasiocarpa* may be present in the tree layer or as reproduction, but not in such abundance to indicate eventual replacement of aspen dominance in the overstory. A tall shrub layer consisting of either *Acer grandidentatum, Prunus virginiana, Amelanchier alnifolia,* or a combination of these shrubs, distinguishes the type from the closely associated POTR/PTAQ c.t., which lacks this shrub layer. The low shrubs *Symphoricarpos oreophilus, Rosa woodsii,* and *Berberis repens* are also frequently present. In addition to the conspicuous dominance of *P. aquilinum* in the undergrowth, other frequently abundant forbs include *Smilacina stellata, Osmorhiza chilensis,* and *Aster engelmannii.* The grasses *Elymus glaucus* and *Bromus carinatus* also frequently provide substantial amounts of cover.

The successional status of this type is uncertain, except that it is unlikely to succeed to conifers. The type may be a grazing-degraded form of the POTR/PRVI/SESE c.t. with which it has many species in common. *P. aquilinum* is not only unpalatable to livestock, it can be poisonous to cattle when eaten in quantity. This unpalatability combined with its ability to spread by creeping rhizomes suggests that it is likely to increase greatly in abundance if its palatable associates are depleted by prolonged excessive grazing. On the other hand, seldom if ever does *P. aquilinum* occur as a minor member of a community. It either tends to dominate the undergrowth or it is absent. This restricted distribution combined with abundance where it does occur suggests that it may have rather specific, and as yet undefined, environmental requirements and represents a distinct climax community type.

Tree productivity in this type generally appears to be moderate to relatively high when compared to other aspen communities. Basal area of aspen ranged from 113 to 174 ft^2/acre (25.8 to 40.0 m^2/ha), and averaged 136 ft^2/acre (31.2 m^2/ha). Site index at 80 years ranged from 45 to 69 ft (13.7 to 21.0 m), and averaged 59 ft (18 m). Conifer production was negligible. Aspen suckering beneath the mature overstory was highly variable but averaged a moderate 1,900/acre (4 700/ha); only one-third of these were in the 1- to 4.6-ft (0.3- to 1.4-m) size class.

Undergrowth productivity also varies widely but appears to be generally high. Forage productivity, however, may be low to moderate. A substantial portion of the undergrowth usually consists of the unpalatable fern, *P. aquilinum.* Annual production of undergrowth in the five stands sampled ranged from 836 to 3,792 lb/acre (938 to 4 256 kg/ha) and averaged 2,068 lb/acre (2 320 kg/ha). Over 85 percent of this consisted of forbs (including *P. aquilinum*), with the remainder divided between the shrubs and graminoid vegetation classes. About a third of this undergrowth comprised desirable forage species, a third intermediate, and a third was classified as least desirable. Although the type may have considerable wildlife habitat benefits because of its multilayered cover of trees, tall shrubs, and herbs, livestock grazing values may be only moderate because of the amount of unpalatable species.

Aspen communities containing an abundance of *P. aquilinum* in the undergrowth have also been identified in northwestern Colorado on the west slope of the Park Range by Bunin (1975) and on the White River National Forest by Hoffman and Alexander (1983); neither of these reports indicated the presence of a tall shrub stratum. Hoffman and Alexander (1980), however, describe a *P. tremuloides/P. aquilinum* habitat type for the Routt National Forest in which almost half of the stands contain a tall shrub stratum consisting of *A. alnifolia* or *P. virginiana* or both, a low shrub layer, and a herb layer containing species typical of our POTR/ACGR/PTAQ c.t. The most conspicuous difference was the abundance of *Carex geyeri* in their stands and the absence of this sedge in ours.

Populus tremuloides/Prunus virginiana/Senecio serra Community Type (POTR/PRVI/SESE c.t.)

This is one of the more common community types, especially in northern Utah. Of the 114 stands that we sampled in this type, approximately a third were in the Bear River Range in extreme northern Utah, a third along the Wasatch Range, and about a fourth southward on portions of the Uinta National Forest east of Provo. Only a few scattered stands were found in the southern half of the State. The type occurs most frequently at intermediate elevations; three-fourths of the sampled stands were between 6,000 and 8,000 ft (1 830 and 2 440 m). It occurred most frequently on sandstone- and limestone-derived soils and on moderately steep slopes that had slightly concave to undulating topography. Slope aspect apparently is not restrictive.

The vegetation of this extensive northern Utah type has a pronounced multilayered structure. Below the virtually pure aspen canopy, a layer of tall shrubs, a layer of low shrubs, and a complex of forbs and graminoids contribute to the high degree of structural diversity (fig. 2). The conspicuous presence of either *Prunus virginiana, Amelanchier alnifolia*, and occasionally *Acer grandidentatum* identify this as part of the tall shrub undergrowth type. The low shrub layer is usually dominated by *Symphoricarpos oreophilus*, with lesser amounts of *Rosa woodsii*, and *Berberis repens*; sometimes *Pachistima myrsinites* is conspicuous. *Elymus glaucus* and *Bromus carinatus* are commonly abundant grasses. Tall-growing forbs such as *Senecio serra, Agastache urticifolia, Aster engelmannii*, and *Rudbeckia occidentalis* are prominent in the herbaceous layer. The epithet species *S. serra* need not be present as long as other members of the tall forb group are present in appropriate amounts (refer to key instructions). *Valeriana occidentalis* also may inhabit little-disturbed stands of this type in noticeable abundance. Various species of *Lathyrus* as well as *Vicia americana*, when abundant, occasionally tend to blanket the low shrubs and herbs.

The POTR/PRVI/SESE c.t. usually represents a climax aspen community type, one that reflects a specific aspen habitat type. Conceivably, under active invasion by conifers, stands identified as this type might be considered seral communities on the *Abies lasiocarpa/Osmorhiza chilensis* habitat type described by Mauk and Henderson (1984), based on common occurrence of certain undergrowth species. Abusive grazing within the POTR/PRVI/SESE c.t. would tend to decrease appreciably the amount of palatable forbs and shrubs, and increase the dominance of the grasses *E. glaucus, B. carinatus*, and *Poa pratensis* (sheep grazing), or such forbs as *R. occidentalis, Lathyrus* spp., and *V. americana* (cattle grazing). In some cases, *S. serra* also may increase substantially under cattle use. Extreme and prolonged grazing could lead to a depauperate undergrowth consisting largely of such annuals as *Nemophila breviflora, Polygonum douglasii*, or *Galium bifolium*. Tree productivity on this common type appears to be generally low to moderate, with occasional stands being fairly high. The basal area of aspen on the 42 intensively sampled stands ranged from 45 to 202 ft^2/acre (10.4 to 46.4 m^2/ha) and averaged 121 ft^2/acre (27.9 m^2/ha). Site index at 80 years for aspen ranged from 31 to 68 ft (9.4 to 20.7 m) and averaged 47 ft (14.4 m). Usually conifer production was negligible. Aspen reproduction in mature stands ranged from virtually none to over 22,000/acre (55 000/ha). The average was a comparatively high 3,800/acre (9 500/ha). About a third of these suckers were in the 1- to 4.6-ft (0.3- to 1.4-m) size class.

Although quite variable, the undergrowth is generally moderately abundant. Because a high proportion of this undergrowth usually consists of palatable forage plants, the type is fairly productive livestock range. Annual undergrowth production on the sampled stands ranged from 509 to 2,341 lb/acre (572 to 2 627 kg/ha) and averaged 1,141 lb/acre (1 281 kg/ha). This was fairly well distributed among the different vegetation classes: an average 30 percent in the shrub class, 48 percent forbs, and

Figure 2.—The structurally diverse *Populus tremuloides/Prunus virginiana/Senecio serra* c.t. is common in northern Utah. This stand on a southwest exposure in Big Cottonwood Canyon east of Salt Lake City has a dense *P. virginiana* tall shrub layer, a low shrub layer of *Symphoricarpos oreophilus* and *Pachistima myrsinites*, and an herb layer dominated by tall forbs.

22 percent graminoids. Of the undergrowth cover, 95 percent comprised species considered either desirable (55 percent) or intermediately desirable (40 percent) forage plants. Thus, this type is relatively good livestock range and provides good wildlife habitat because of its great amount of structural diversity.

Communities similar to the POTR/PRVI/SESE c.t. are widely encountered in surrounding States. The *P. tremuloides/A. alnifolia-S. oreophilus* c.t. described by Mueggler and Campbell (1982) for southeastern Idaho contains stands similar to our type. Hoffman and Alexander (1980) described a *P. tremuloides/S. oreophilus* habitat type in northwestern Colorado that apparently includes stands similar to our POTR/PRVI/SESE c.t.; about half of the stands within their type have a tall shrub component of *P. virginiana* or *A. alnifolia* or both, a low shrub stratum of *S. oreophilus*, and an herbaceous layer fairly similar to that in our type. Bunin (1975) described a *P. tremuloides/Quercus gambelii—A. alnifolia-Thalictrum fendleri* association on the west slope of the Park Range in Colorado that is similar except for the absence of *Q. gambelii* in our stands. In addition, a *P. tremuloides/S. oreophilus* community with similar tall shrub, low shrub, and tall herbaceous species was observed in northeastern Nevada (Lewis 1975).

Populus tremuloides/Prunus virginiana/Carex geyeri Community Type (POTR/PRVI/CAGE c.t.)

The POTR/PRVI/CAGE c.t. is a minor type that is most prevalent in northern Utah. We sampled 12 stands along the Bear River Mountains, southward along the Wasatch Range, and intermittently eastward along the south slope of the Uinta Mountains. A single stand was in the Pine Valley Mountains in extreme southwestern Utah and one in the Abajo Mountains of southeastern Utah, which reflects its infrequent but wide distribution. The stand in the Abajo Mountains was of questionable placement in this community type. The sampled stands occurred at elevations between 5,500 and 8,700 ft (1 680 and 2 650 m) and did not appear restricted by slope exposure or soil parent material.

The vegetation in this type reflects a somewhat drier environment than either the POTR/PRVI/SESE or POTR/ACGR/PTAQ c.t.'s, the other two tall shrub undergrowth types within this cover type group. Although a variety of conifers may be present, none are abundant. The stands within this community type are structurally diverse with multiple layers of vegetation. Below the aspen overstory exists a tall shrub component in which *Amelanchier alnifolia* or *Prunus virginiana* or both usually predominate; occasionally *Acer grandidentatum* is a major part of this layer. A low shrub layer is usually conspicuous with an abundance of *Symphoricarpos oreophilus* and often substantial amounts of *Berberis repens, Pachistima myrsinites*, and *Rosa woodsii*. The herbaceous layer is characterized by an abundance of the graminoids *Carex geyeri* or *Stipa occidentalis* or both. Species and amounts of forbs vary appreciably but can include considerable amounts of *Thalictrum fendleri, Smilacina stellata, Geranium viscosissimum, Achillea millefolium*, and occasionally *Lupinus argenteus*.

This is primarily a climax community type. In some cases, however, with active invasion of *Abies lasiocarpa*, stands classified in this type might represent seral communities in the *A. lasiocarpa/B. repens* habitat type if in northern Utah (Mauk and Henderson 1984) or in the *A. lasiocarpa/C. geyeri* habitat type if in central or southern Utah (Youngblood and Mauk 1985), judging from species similarity in the undergrowth. Abusive livestock grazing in this type may lead to composition changes that favor *Poa pratensis, Astragalus miser, A. millefolium*, and possibly *Lathyrus* spp.

The potential for wood fiber production on this minor type appears fairly low. Basal area of trees on seven sampled stands ranged from 71 to 155 ft^2/acre (16.2 to 35.7 m^2/ha), and averaged 104 ft^2/acre (23.8 m^2/ha). About 98 percent of this basal area was aspen, and 2 percent was conifers. Site index for the aspen at 80 years ranged from 34 to 62 ft (10.4 to 18.9 m) and averaged 46 ft (14.1 m). Aspen reproduction in these mature stands varied greatly, averaging 2,200/acre (5 500/ha). About a third of these were suckers less than 12 inches (3 dm) high and the remainder were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

The undergrowth appears somewhat better suited for cattle than for sheep grazing. Overall productivity is moderate, and forage suitability appears generally good. Current annual growth ranged between 609 and 1,838 lb/acre (684 and 2 062 kg/ha) and averaged 975 lb/acre (1 094 kg/ha). This growth consisted of 46 percent tall and low shrubs, 25 percent forbs, and 29 percent graminoids. Over 95 percent of the undergrowth cover consisted of plants with at least intermediate suitability as livestock forage. Therefore, overall forage production is fairly good. The type has relatively high value as wildlife habitat because of the great amount of structural diversity contributed by the abundant tall and low shrubs.

Types similar to the POTR/PRVI/CAGE c.t. have been noted in southeastern Idaho and in western Wyoming. Mueggler and Campbell (1982) defined a *P. tremuloides/A. alnifolia-Calamagrostis rubescens* c.t. in Idaho, and Youngblood and Mueggler (1981) a *P. tremuloides/P. virginiana* c.t. in Wyoming that structurally and compositionally resembles the Utah type. In both the Idaho and Wyoming types, however, *C. rubescens* is abundant in the herbaceous layer rather than the *C. geyeri* or *S. occidentalis* or both that are present in the Utah type.

Populus tremuloides/Sambucus racemosa Community Type (POTR/SARA c.t.)

Although this is a relatively minor community type, it is fairly well distributed over the higher mountains of Utah. The 16 stands sampled occurred primarily on the Wasatch-Cache, Uinta, and Manti-LaSal National Forests. The type appeared most frequently on midslope to upper-slope positions on sedimentary soils. All but one of the stands occurred at elevations exceeding 8,000 ft (2 440 m). Half the stands grew at elevations over 9,000 ft (2 740 m).

Abies lasiocarpa and *Picea engelmannii* occasionally are found in this type but never in abundance. *Sambucus*

racemosa or *S. cerulea* form a conspicuous part of the undergrowth; other shrubs are generally scarce, with the possible exception of *Salix scoulerana*. The grasses *Bromus carinatus* and *Agropyron trachycaulum* are usually present and sometimes abundant. Certain members of the tall forb group, such as *Mertensia arizonica*, *Delphinium occidentale*, *Osmorhiza occidentalis*, *Polemonium foliosissimum*, and *Rudbeckia occidentalis*, are often conspicuous and may be abundant, as are *Thalictrum fendleri* and *Valeriana occidentalis*.

Although the successional status is uncertain, the type probably reflects a distinct environment or habitat type. Coniferous forests adjacent to these high elevation communities usually are dominated by *A. lasiocarpa*. Prolonged overgrazing can lead to a change in undergrowth composition that favors *M. arizonica* (if grazed midsummer or late summer), *R. occidentalis*, and possibly *Lathyrus* spp. Overgrazing will also increase the amount of exposed soil and such annuals as *Nemophila breviflora, Polygonum douglasii*, and *Galium bifolium*.

The type is relatively productive for trees, even though aspen apparently does not reproduce well beneath the existing canopy. Tree basal area on eight sampled stands ranged from 70 to 211 ft^2/acre (16.1 to 48.5 m^2/ha) and averaged 150 ft^2/acre (34.5 m^2/ha). Virtually all of this consisted of aspen. Aspen site index at 80 years was moderate, averaging 54 ft (16.5 m) and ranging from 38 to 65 ft (11.6 to 19.8 m). Aspen suckers averaged only about 900/acre (2 200/ha), with two-thirds in the 1- to 4.6-ft (0.3- to 1.4-m) size class.

The undergrowth typically consists of a moderately productive mixture of shrubs, forbs, and grasses. Annual production ranged from 491 to 1,924 lb/acre (552 to 2 159 kg/ha) and averaged 1,072 lb/acre (1 204 kg/ha). Of this, 35 percent was shrubs, 52 percent forbs, and 13 percent graminoids. About half of the undergrowth consisted of desirable forage species and a third was of intermediate forage suitability. The type appears to have relatively moderate value both as livestock range and as wildlife habitat.

Although *S. racemosa* and *S. cerulea* may occur occasionally as minor shrubs in aspen stands elsewhere, they have not been reported before as major species characterizing a specific community type.

Populus tremuloides/Symphoricarpos oreophilus/Senecio serra Community Type (POTR/SYOR/SESE c.t.)

The POTR/SYOR/SESE c.t. was the most frequently encountered aspen type in Utah—almost 12 percent of stands sampled. It appears to be a predominantly northern Utah community type; over three-fourths of the stands were on the Wasatch-Cache and Uinta National Forests (fig. 3). The majority were encountered on the Bear River and Wasatch Ranges. Stands were also found in the San Pitch Mountains, the Pavant Range, and occasionally in the Abajo and LaSal Mountains. It was conspicuously absent from the high plateaus of southern Utah.

This is typically an intermediate-elevation community type that clearly demonstrates the effect of latitude upon elevational distribution of a plant community. On the Wasatch-Cache National Forest in northern Utah, stands within this type occurred at elevations between 6,200 and 8,800 ft (1 890 and 2 680 m). On the Manti-LaSal National Forest in central Utah, an average 2° latitude farther south, the type in general occurred at elevations about 1,000 ft (300 m) higher, between 7,700 and 9,700 ft (2 350 and 2 960 m) elevation. The type appeared most frequently on slopes of less than 25 percent steepness and on soils derived from sedimentary parent materials, primarily sandstones.

The POTR/SYOR/SESE c.t. vegetation consists of three distinct strata: an overstory of pure aspen, a low shrub layer, and an herbaceous layer of a rich mixture of tall and low-growing plants. Tall shrubs such as *Amelanchier alnifolia* and *Prunus virginiana* occasionally may be present, but they are never abundant. The low shrub stratum is dominated exclusively by *Symphoricarpos oreophilus*. The herbaceous undergrowth is typified by a tall forb mixture that varies considerably between stands. The most commonly associated tall forbs are *Rudbeckia occidentalis, Senecio serra, Agastache urticifolia, Mertensia arizonica, Aster engelmannii*, and *Polemonium foliosissimum*. The forb *S. serra* was selected to represent this tall forb complex in the type name, even though it is not present in all stands within the type. Other forbs frequently present in substantial amounts include *Hackelia floribunda, Osmorhiza chilensis, Thalictrum fendleri*, and *Valeriana occidentalis*. Usually the prominent grasses are *Bromus carinatus, Agropyron trachycaulum*, and *Elymus glaucus*. Species diversity within this community type is often great.

We consider this primarily an extensive climax community type, thus representing a distinct aspen habitat type. The presence of conifers is usually accidental. However, when stands are classified to this type because of current lack of conifers, yet conifers appear able to actively invade, such stands likely will be successional within the *Abies lasiocarpa/O. chilensis* habitat type in northern Utah (Mauk and Henderson 1984) or within the *A. lasiocarpa/Aconitum columbianum* habitat type in central Utah (Youngblood and Mauk 1985). Abusive livestock grazing usually simplifies the undergrowth appreciably. Extended heavy use by sheep will likely shift species composition from the more palatable tall forbs and *S. oreophilus* to that dominated by *E. glaucus, B. carinatus*, and possibly *Poa pratensis*. Eventually it could change to a depauperate condition where only unpalatable perennials and such annuals as *Nemophila breviflora, Polygonum douglasii*, and *Collomia linearis* remain. Excessive cattle grazing may shift composition to dominance by *R. occidentalis, Vicia americana, Lathyrus* spp., and possibly *M. arizonica*, and then to a depauperate annual condition if such abuse persists. The dense blanket of *V. americana* and *Lathyrus* spp. sometimes found in these stands probably is an artifact of past livestock use.

The amount of wood produced in this common community type varies greatly between stands. In general, the type is relatively low in fiber production. The tree basal area on 42 stands ranged between 14 and 233 ft^2/acre

Figure 3.—The *Populus tremuloides/Symphoricarpos oreophilus/Senecio serra* c.t. such as this stand on the Uinta National Forest near the Payson Guard Station, is a prominent northern Utah aspen type. The undergrowth generally consists of a rich mixture of tall and low forbs, graminoids, and low shrubs dominated by *S. oreophilus*.

(3.3 and 53.4 m^2/ha) and averaged 115 ft^2/acre (26.4 m^2/ha). Only 2 percent of this basal area consisted of conifers. Aspen site index at 80 years ranged from 26 to 71 ft (7.9 to 21.6 m) and averaged a moderately low 48 ft (14.5 m). Aspen reproduction in these mature stands was about equally divided between suckers less than 1 ft (0.3 m) high and those over this height. Number of suckers was highly variable, from almost complete absence to over 20,000/acre (50 000/ha), but averaged a moderate 2,700/acre (6 600/ha).

The quantity of undergrowth is also variable but generally consists of a fairly productive mixture of different vegetation classes. Annual production averaged 1,340 lb/acre (1 504 kg/ha) and ranged from 386 to 2,654 lb/acre (434 to 2 956 kg/ha). An average 20 percent of this consisted of shrubs, principally *S. oreophilus*, 55 percent of forbs, and 25 percent of graminoids. Almost 90 percent of the undergrowth was comprised of species that are considered desirable (51 percent) or of intermediate forage suitability (37 percent). The type, therefore, is fairly good summer range for both sheep and cattle. Wildlife habitat values may be less than optimum because of the lack of a tall shrub layer.

Aspen communities with undergrowth of only a low shrub stratum primarily of *S. oreophilus* and an herbaceous layer with good representation of tall forbs are fairly widespread. Mueggler and Campbell (1982) described a *P. tremuloides/S. oreophilus-R. occidentalis* c.t. in southeastern Idaho that is similar to our Utah type except their stands appear to be more severely altered by abusive grazing. A *P. tremuloides/S. oreophilus* c.t. was identified for western Wyoming that is also fairly similar (Youngblood and Mueggler 1981). About a third of the stands in the more generalized *P. tremuloides/S. oreophilus* habitat type described for the Routt National Forest (Hoffman and Alexander 1983) and about a fourth of those in the *P. tremuloides/S. oreophilus* habitat type described for the White River National Forest (Hoffman and Alexander 1980) in northwestern Colorado appear structurally and compositionally similar to our POTR/SYOR/SESE c.t.

Populus tremuloides/Symphoricarpos oreophilus/Carex geyeri Community Type (POTR/SYOR/CAGE c.t.)

This relatively common community type is widely distributed across all National Forests in Utah. Stands were encountered at elevations ranging from 6,100 to 9,400 ft (1 860 to 2 870 m). The type occurred on all exposures on mountain slopes usually less than 25 percent in steepness. About half the stands in this type grew on soils of sandstone origin, and about a fourth on granitic soils.

The indicator species *Carex geyeri*, *Carex rossii*, and *Stipa occidentalis* are believed to reflect similar environmental situations, yet they do not necessarily frequent the same geographical areas. *Carex geyeri* is a primary undergrowth component only on the Uinta, Ashley, and Manti-LaSal National Forests; *C. rossii* and *S. occidentalis* prevail as indicator species on the Fishlake and Dixie National Forests where *C. geyeri* is usually absent. This presents a dilemma in naming community types: either we unnecessarily increase the number of community type names, or we select a single species to reflect the undergrowth portion of the epithet even though it may not be present in all areas. We have chosen the latter; *C. geyeri* is used in the epithet to represent all three species of graminoids.

The POTR/SYOR/CAGE c.t. has a considerably less diverse assemblage of species than the POTR/SYOR/SESE c.t. Both types are essentially three layered, with an aspen-dominated overstory, and a *Symphoricarpos oreophilus* shrub stratum. The herbaceous undergrowth in the POTR/SYOR/CAGE c.t., however, is less complex. This undergrowth usually has an abundance of graminoids accompanied by low-growing forbs. As noted above, we consider *C. geyeri*, *C. rossii*, and *S. occidentalis* to more or less indicate equivalent abiotic environments, even though they may react somewhat differently to disturbance such as grazing. Frequently *Agropyron trachycaulum* and *Poa pratensis* are also common graminoids. Some of the more common forbs include

Thalictrum fendleri, Lupinus argenteus, and *Geranium viscosissimum.* The dominant *S. oreophilus* in the shrub layer is frequently accompanied by *Rosa woodsii* and *Berberis repens.*

We believe that this type is essentially a climax community type representing a fairly broad POTR/SYOR/CAGE habitat type. The occasional presence of *Pseudotsuga menziesii* or *Abies lasiocarpa* and associated species suggests that it may also be considered a seral community within either of those coniferous forest series, possibly the *P. menziesii/S. oreophilus, P. menziesii/B. repens,* or *A. lasiocarpa/B. repens* habitat types (Mauk and Henderson 1984; Youngblood and Mauk 1985). Overgrazing within the POTR/SYOR/CAGE c.t. probably shifts community composition toward greater abundance of *Poa pratensis, Sitanion hystrix, Astragalus miser, Taraxacum officinale,* and *Achillea millefolium.*

This type has a fairly high potential for wood production, yet only moderate potential for the production of undergrowth. Tree basal area on 14 sampled stands ranged from 74 to 292 ft^2/acre (16.9 to 67.0 m^2/ha) and averaged 165 ft^2/acre (37.8 m^2/ha). Virtually all of this consisted of aspen. Site index at 80 years for aspen ranged from 35 to 75 ft (10.7 to 22.9 m) and averaged a moderate 50 ft (15.3 m). Aspen suckers averaged a moderate 1,700/acre (4 100/ha), slightly over half of which were in the 1- to 4.6-ft (0.3- to 1.4-m) size class.

Annual production of undergrowth ranged from 331 to 1,990 lb/acre (372 to 2 234 kg/ha), and averaged a moderate 1,071 lb/acre (1 202 kg/ha). This production was divided among major vegetation classes as follows: 23 percent shrubs, 44 percent forbs, and 33 percent graminoids. Over 50 percent of the vegetation fell into the desirable forage suitability class, and less than 10 percent was in the least desirable class. The type is relatively good livestock summer range, perhaps more suited to cattle than to sheep. The lack of a tall shrub stratum reduces structural diversity and consequently somewhat diminishes the value of the type as wildlife habitat.

Aspen communities similar to this type have been observed elsewhere. Schlatterer (1972) identified a *P. tremuloides/S. oreophilus-C. geyeri* habitat type in the Sawtooth area of south-central Idaho. A similar *P. tremuloides/S. oreophilus-Calamagrostis rubescens* community type, with *C. rubescens* replacing *C. geyeri* as the principal graminoid, occurs in southeastern Idaho (Mueggler and Campbell 1982). Some of the stands occurring in the generalized *P. tremuloides/S. oreophilus* habitat type in northwestern Colorado (Hoffman and Alexander 1983) resemble those in our POTR/SYOR/SESE c.t.

Populus tremuloides/Symphoricarpos oreophilus/Festuca thurberi Community Type (POTR/SYOR/FETH c.t.)

This minor type, sampled by only seven stands, is restricted to central and southern Utah. Three stands were encountered on the Fishlake Plateau and four on the Aquarius Plateau. These stands were at elevations between 8,600 and 9,400 ft (2 620 and 2 870 m) and on soils derived either from volcanic or granitic parent materials.

The type is characterized by a distinct shrub layer dominated by *Symphoricarpos oreophilus* and a rather simple herbaceous layer in which *Festuca thurberi* is a conspicuous dominant. Although conifers are not abundant, *Pseudotsuga menziesii* frequently will be found in this type. The shrub stratum often contains appreciable amounts of *Berberis repens* and *Rosa woodsii.* Grasses that may be abundantly associated with *F. thurberi* include *Bromus anomalus* and *Stipa occidentalis.* Forbs are ordinarily sparse; those most likely to form a substantial part of the undergrowth are *Lathyrus* spp., *Vicia americana, Taraxacum officinale,* and *Thalictrum fendleri.*

The few stands sampled in the POTR/SYOR/FETH c.t. appeared to reflect considerable past grazing pressure, judging from the abundance of *T. officinale, V. americana,* and *Lathyrus* spp. The type appears to represent primarily a POTR/SYOR/FETH habitat type, but with appreciably altered species composition. The amount of *P. menziesii* occurring in some stands suggests that they may be seral within the *P. menziesii* forest series.

Only two stands within this type were sampled to assess productivity. This limited sample suggests that wood fiber production is relatively high. Tree basal area was 160 and 178 ft^2/acre (36.8 and 40.9 m^2/ha), and the 80-year site index for aspen was 52 and 63 ft (15.8 and 19.2 m). Virtually all of the basal area was aspen. Reproduction of aspen in these mature stands was very low, averaging less than 180 suckers/acre (450/ha).

Undergrowth production was a relatively low 405 and 774 lb/acre (455 and 869 kg/ha). A high proportion of this, an average 56 percent, consisted of shrubs, 27 percent was forbs, and 17 percent was graminoids. A high proportion of the undergrowth consisted of vegetation in the desirable and intermediate forage suitability categories. Thus, although the type appears to produce high quality livestock forage, the quantity is relatively low. The absence of a tall shrub layer somewhat reduces the value of this type as wildlife habitat.

Langenheim (1962) reported aspen stands with the tussock *F. thurberi* as a major grass component in the undergrowth in only one other location, the Crested Butte area of west-central Colorado. Some of the communities she described contained a low shrub stratum dominated by *S. oreophilus* and an herbaceous layer with appreciable amounts of *F. thurberi.*

Populus tremuloides/Juniperus communis/Carex geyeri Community Type (POTR/JUCO/CAGE c.t.)

The POTR/JUCO/CAGE type was encountered principally on the Wasatch-Cache and Ashley National Forests where 70 stands were sampled. Over three-fourths of the occurrences were in the Uinta Mountains of northeastern Utah. The type was occasionally encountered in central and southern Utah on the Fishlake and Aquarius Plateaus and in the Tushar Mountains. *Carex rossii* and *Stipa occidentalis* were the equivalent indica-

tor graminoids in these more southerly locations rather than *Carex geyeri* (see the POTR/SYOR/CAGE c.t. section). The type usually occurred at the intermediate and upper elevations ranging from 7,500 to 9,100 ft (2 290 to 2 770 m). Although the type was found most frequently on gentle slopes, it does not appear to be restricted by either slope exposure or soil parent material.

The characterizing species for the type are the conspicuous *Juniperus communis* in the shrub stratum and the dominant graminoids *C. geyeri* or *S. occidentalis* or both in the herb stratum (fig. 4). In central and southern Utah, *C. rossii* usually replaces *C. geyeri* in the association. *Juniperus communis* generally grows as distinct low, compact clumps widely scattered beneath the aspen canopy. These clumps frequently are interspersed with *Symphoricarpos oreophilus* and *Berberis repens*, which may form a substantial part of the shrub layer. The herb layer usually is fairly simple. In addition to the typifying graminoids, such forbs as *Astragalus miser, Geranium viscosissimum, Lupinus argenteus, Achillea millefolium*, and *Thalictrum fendleri* may grow in substantial amounts. Conifers, usually *Pinus contorta* or *Pseudotsuga menziesii*, are occasionally present in minor amounts.

Stands within this type are ordinarily in a stable aspen condition. In those cases where conifers appear able to invade, the stands may be a successional stage within the *Abies lasiocarpa/J. communis, A. lasiocarpa/B. repens*, or possibly *P. menziesii/B. repens* habitat types described by Mauk and Henderson (1984). Excessive livestock grazing will likely lead to substantial increases in the amount of *Taraxacum officinale, A. miser, A. millefolium*, and possibly *J. communis* at the expense of the more palatable and less tenacious forage species.

Although the average basal area produced by aspen within this type appears moderate, its site index is low. Basal area of the 11 stands sampled for productivity ranged from 47 to 234 ft^2/acre (10.9 to 53.6 m^2/ha) and averaged 146 ft^2/acre (33.5 m^2/ha). This basal area was 98 percent aspen. Site index at 80 years for the aspen ranged from 23 to 68 ft (7.0 to 20.7 m) and averaged a low 45 ft (13.7 m). Aspen reproduction within these stands was also low, averaging only 896 suckers/acre (2 215/ha). Two-thirds of these suckers were in the 1- to 4.6-ft (0.3- to 1.4-m) height class. The amount of undergrowth production within this type is relatively low and rather evenly distributed among the different vegetation categories. Total production ranged from 141 to 1,031 lb/acre (158 to 1 158 kg/ha) and averaged only 597 lb/acre (670 kg/ha). This consisted of 42 percent graminoids, 4 percent forbs, and the remainder was shrubs. Of the undergrowth, 53 percent was in the highest forage suitability class, and almost 10 percent was in the lowest class. The type has relatively low potential for livestock forage production. Value as habitat for wildlife appears only moderate because of its modest amount of structural diversity.

Aspen communities with a low shrub layer dominated by *J. communis* have been reported from two separate areas in Wyoming. Wirsing and Alexander (1975) identified a *P. tremuloides/C. geyeri* habitat type on the Medicine Bow National Forest in southeastern Wyoming similar to our type in that *J. communis* was the principal shrub and *C. geyeri* characterized the herbaceous layer. However, their type differed by the absence of *S. oreophilus* and abundance of *Arnica cordifolia* and *Osmorhiza depauperata*. A *P. tremuloides/J. communis* community type was described for western Wyoming (Youngblood and Mueggler 1981) in which *J. communis* dominated the shrub layer, but differed from our type by the prominence of the associated shrub *Shepherdia canadensis* and by the lack of characterizing graminoids in the rather depauperate herbaceous layer.

Figure 4.—The *Populus tremuloides/Juniperus communis/Carex geyeri* c.t. is prominent in the Uinta Mountains of northeastern Utah. In this typical stand near the Kaler Hollow Guard Station on the Ashley National Forest, *J. Communis* is the conspicuous low shrub. The herbaceous growth consists primarily of such graminoids as *C. geyeri* and such forbs as *Astragalus miser* and *Lupinus argenteus*.

Populus tremuloides/Juniperus communis/ Sitanion hystrix Community Type (POTR/JUCO/SIHY c.t.)

Though not common, this community type was encountered intermittently across most of the National Forests of Utah. We sampled 21 stands within the type. The type occurred most frequently in the Uinta Mountains in northeastern Utah but extended southward to the Aquarius and Markagunt Plateaus in southern Utah. This is a mid-elevation type with over 80 percent of the stands in the 8,000 to 9,000 ft (2 440 to 2 740 m) elevation zone. Most of the stands grew on soils derived either from granite or sandstone.

Vegetation in the POTR/JUCO/SIHY c.t. reflects a drier environment than that occupied by the POTR/JUCO/CAGE c.t. The shrub layer is typified by the dominance of *Juniperus communis* or *Artemisia tridentata* or both. Other shrubs frequently present in noticeable amounts are *Symphoricarpos oreophilus* and *Berberis repens*. The herbaceous undergrowth is comparatively poor and is typified by the substantial presence of one or more of the grasses *Sitanion hystrix*, *Stipa comata*, and *Stipa lettermanii*. Forbs are generally sparse. Most frequently encountered are *Achillea millefolium*, *Taraxacum officinale*, and *Lupinus argenteus*. The latter at times forms the major part of the undergrowth biomass.

This community type is primarily a relatively dry-site, stable aspen type. In some situations, where *Pinus ponderosa* or *Pseudotsuga menziesii* are actively invading the aspen stand, the type may be a seral stage within the *P. ponderosa/Festuca idahoensis* habitat type in northern Utah (Mauk and Henderson 1984), or possibly the *P. menziesii/B. repens* habitat type farther south (Youngblood and Mauk 1985). Abusive grazing in this type could lead to an increase in the shrubs *A. tridentata* and *J. communis*, the forbs *A. millefolium* and *T. officinale*, and possibly in the grass *Poa pratensis*.

Production was not measured in this type. It probably is a less productive livestock range and wildlife habitat than the POTR/JUCO/CAGE c.t. because of a drier environment and lower proportion of vegetation in the desirable forage suitability class. Wood production is also likely below that of the POTR/JUCO/CAGE c.t. Undergrowth production probably averages less than 535 lb/acre (600 kg/ha) and tree production less than 130 ft^2/acre (30 m^2/ha).

Although aspen communities with a low shrub layer dominated by *J. communis* have been reported elsewhere (Youngblood and Mueggler 1981; Wirsing and Alexander 1975), none have herbaceous undergrowth composition similar to that in our POTR/JUCO/SIHY c.t.

Populus tremuloides/Symphoricarpos oreophilus/Bromus carinatus Community Type (POTR/SYOR/BRCA c.t.)

This infrequent community type was represented by only 12 stands principally in northern Utah on the Bear River and Wasatch Ranges. One stand was in the Abajo Mountains in southeastern Utah. The type occurred at elevations ranging from 6,400 to 8,600 ft (1 950 to 2 620 m), on all exposures, but primarily on sandstone and quartzite derived soils.

Vegetation of the POTR/SYOR/BRCA c.t. reflects appreciable alteration because of livestock grazing. The vegetation consists essentially of three strata: trees, low shrubs, and herbs. The tree layer is virtually pure aspen; conifers are present occasionally but only in minor amounts. The shrub layer may be a mixture of various species, but *Symphoricarpos oreophilus* is the only one that has both high constancy and abundance. *Amelanchier alnifolia* and other tall shrubs sometimes may be present but never in sufficient abundance to form a definite stratum of tall shrubs. The herbaceous undergrowth is characterized by the abundance of the tall grasses *Bromus carinatus* or *Elymus glaucus* or both; *Agropyron trachycaulum* is usually present in substantial quantities. Although a variety of forbs may be present in any one stand, constancy between stands of any single species is generally low. *Geranium viscosissimum* and *Lathyrus* spp. appear to be the most representative forbs.

We believe that this type is primarily a seral stage leading to a climax aspen POTR/SYOR/SESE c.t. The paucity of tall forbs that commonly exist in the POTR/SYOR/SESE c.t. and the proportionately greater role of *B. carinatus* and *E. glaucus* in the undergrowth are attributed to grazing influences, probably by sheep. Heavy, continued grazing pressure could lead to yet more pronounced changes, such as a decrease in *S. oreophilus*, a replacement of desirable perennial herbs with yet greater amounts of *Poa pratensis*, *Taraxacum officinale*, and possibly *Lathyrus* spp. Where conifers appear able to actively invade, such stands may be a seral stage in the *Abies lasiocarpa/Osmorhiza chilensis* habitat type (Mauk and Henderson 1984).

Only two stands were sampled for productivity. Based on this small sample, wood production appears to be fairly low. Basal area of trees was a low 97 and 109 ft^2/acre (22.3 and 25.1 m^2/ha); 94 percent of this was aspen and the remainder was conifers. Aspen site index at 80 years was a moderate 48 and 62 ft (14.6 and 18.9 m). Aspen reproduction was moderate at approximately 2,600 suckers/acre (6 500/ha), almost 40 percent of which were 1 to 4.6 ft (0.3 to 1.4 m) high.

Undergrowth production was low to moderate. Total production within the two stands was 463 and 1,583 lb/acre (519 and 1 777 kg/ha). This was distributed among vegetation classes as follows: 12 percent shrubs, 29 percent forbs, and 59 percent graminoids. Of the total undergrowth, 97 percent was in the desirable and intermediate forage suitability groups. This seral type produces less forage of a considerably different character than the successionally related POTR/SYOR/SESE c.t.,

which tends to be dominated by tall forbs rather than by grasses. The POTR/SYOR/BRCA c.t. is relatively good range for cattle and somewhat less desirable for sheep because of the prominence of grasses. The absence of a tall shrub stratum and somewhat meager stratum of low shrubs restricts the value of this type as wildlife habitat.

This specific seral community type has not been reported elsewhere. However, it is believed to represent a grazing-degraded type leading to a POTR/SYOR/SESE climax community type, which appears rather widespread. Communities similar to POTR/SYOR/SESE type occur in southeastern Idaho (Mueggler and Campbell 1982), western Wyoming (Youngblood and Mueggler 1981), and western Colorado (Hoffman and Alexander 1980, 1983).

Populus tremuloides/Symphoricarpos oreophilus/Poa pratensis Community Type (POTR/SYOR/POPR c.t.)

We identified the POTR/SYOR/POPR c.t. on the basis of 30 sampled stands widely scattered from the Bear River Range in extreme northern Utah to the Abajo Mountains in the southeast and the high plateaus in southwestern Utah. The stands were at elevations as low as 6,000 ft (1 830 m) in northern Utah, but were between 7,500 and 8,800 ft (2 290 and 2 680 m) in southern Utah. These stands generally occupied shallow slopes, a wide variety of exposures, and grew on all soils except those derived from granitic parent material.

The vegetation appears considerably degraded by abusive grazing. Although a wide variety of species may be encountered in different stands within this type, few are constant, much less prominent. The vegetation of the type is characterized by the presence of a low shrub layer dominated by *Symphoricarpos oreophilus* and an herb layer comprised predominantly of *Poa pratensis* and *Taraxacum officinale*. Most frequently associated with these are *Berberis repens, Agropyron trachycaulum, Achillea millefolium*, and *Lupinus argenteus*.

The type is a result of a long history of intensive grazing of what probably once were climax POTR/SYOR/CAGE or POTR/SYOR/SESE community types. Although both *P. pratensis* and *T. officinale* are palatable to cattle and sheep, their growth characteristics enable them to withstand intensive grazing remarkably well. These two species are able to increase under abusive grazing because of reduced competition from the more grazing-sensitive species that are equally or even less palatable to livestock. Continued abusive grazing probably will cause depletion of *S. oreophilus* and conversion to a POTR/POPR c.t.

Overall productivity of both trees and undergrowth in this type appears low to moderate. Tree basal area, all aspen, ranged from 96 to 160 ft^2/acre (22.0 to 36.7 m^2/ha) and averaged 117 ft^2/acre (26.9 m^2/ha). Aspen site index at 80 years ranged from 43 to 50 ft (13.1 to 15.2 m) and averaged 47 ft (14.2 m). Aspen reproduction in the sampled stands averaged a low 890 suckers/acre (2 200/ha); two-thirds of these were in the 1- to 4.6-ft (0.3- to 1.4-m) size class.

Undergrowth production ranged from 426 to 1,240 lb/acre (479 to 1 391 kg/ha) and averaged a low to moderate 929 lb/acre (1 042 kg/ha). This was equally distributed among shrubs, forbs, and graminoids. Only 30 percent of the undergrowth was rated as desirable; 65 percent was rated as intermediate forage suitability. Presumably this community type, degraded by abusive livestock grazing, was once considerably more productive of forage than at present. Both overall production and species diversity have undoubtedly decreased. Value of the type as wildlife habitat appears only moderate because of limited structural and low species diversity.

This grazing-induced type is similar to the *P. tremuloides/S. oreophilus-P. pratensis* seral type in southeastern Idaho reported by Mueggler and Campbell (1982).

Populus tremuloides/Juniperus communis/Astragalus miser Community Type (POTR/JUCO/ASMI c.t.)

The POTR/JUCO/ASMI c.t. is a minor and fairly local type that was observed only in the Uinta Mountains of northern Utah. We sampled 10 stands, primarily on easterly and southerly exposures, at relatively high elevations ranging from 8,300 to 9,300 ft (2 530 to 2 830 m). The stands were restricted to sedimentary soils derived from quartzite, sandstone, and limestone parent material.

The vegetation of this type can have considerable species diversity. Occasional conifers may be present, particularly *Pinus contorta*, but they are never abundant. A pronounced low shrub layer is present, usually consisting of a mixture in which *Juniperus communis* is a constant and usually dominant or codominant species. The shrubs *Symphoricarpos oreophilus* and *Berberis repens* frequently occur; in some stands *Arctostaphylos uva-ursi* or *Artemisia tridentata* may be abundant. The herb stratum is typified by the relative abundance of *Astragalus miser*. Other frequently encountered forbs include *Achillea millefolium, Taraxacum officinale*, and *Antennaria microphylla*. Graminoids usually are fairly scarce, with *Agropyron trachycaulum, Leucopoa kingii*, and *Bromus ciliatus* most frequently present.

Judging from the usual abundance of *A. miser, A. millefolium*, and *T. officinale*, this appears to be a seral type created by overgrazing. Occupancy of relatively dry sites and similarities in species composition suggest that the type may be a degraded version of the POTR/JUCO/CAGE c.t. Stands within the type susceptible to *Abies lasiocarpa* invasion may be seral and grazing-altered communities within the *A. lasiocarpa/B. repens* or *A. lasiocarpa/J. communis* habitat types described by Mauk and Henderson (1984).

This type was not sampled for production. However, its successional relationship to the POTR/JUCO/CAGE c.t. suggests that wood productivity is probably fairly low with an aspen site index at 80 years less than 46 ft (14 m). Average undergrowth productivity is also probably quite low, less than 580 lb/acre (650 kg/ha). This undergrowth consists of a high proportion of species that are intermediate to low in forage suitability. The

combination of low productivity and low suitability makes this type poor livestock range. For similar reasons, plus limited structural diversity, the type probably provides relatively poor wildlife habitat.

Aspen communities with a low shrub layer dominated by *J. communis* have been reported for Wyoming (Youngblood and Mueggler 1981; Wirsing and Alexander 1975), but none have herbaceous undergrowth similar to this Utah type.

Populus tremuloides/Veratrum californicum Community Type (POTR/VECA c.t.)

This is a scarce yet identifiably unique community type. We sampled only two stands, one on the north slope of the Uintas in the upper Bear River drainage and the other in the San Pitch Mountains east of Santaquin. These stands occupied moist sites on heavy, deep soils with poor moisture drainage.

The type is readily recognized by an undergrowth dominated by *Veratrum californicum*, a tall, coarse forb. Shrubs are either absent or occur in only trace amounts, thus the vegetation is structurally simple. Associated herbaceous species are those that grow well under fairly moist site conditions, such as *Carex hoodii*, *Phleum alpinum*, and *Rudbeckia occidentalis*.

This appears to represent a climax community type or habitat type. Heavy grazing probably results in an increase in *V. californicum* and *R. occidentalis* at the expense of the more palatable graminoids.

The single stand sampled for productivity within this type suggests that although tree basal area may be low, aspen growth is rapid on these moist sites. Tree basal area in the stand was 71 ft^2/acre (16.4 m^2/ha) and aspen site index at 80 years was 70 ft (21.3 m). Aspen reproduction was a moderate 2,300 suckers/acre (5 700/ha), two-thirds of which were in the 1- to 4.6-ft (0.3- to 1.4-m) size class.

Undergrowth production can be high because lack of soil moisture seldom restricts plant growth. The sampled stand produced 1,582 lb/acre (1 775 kg/ha). Forbs accounted for 34 percent of this, graminoids 65 percent, and shrubs only 1 percent. The type is not very good for livestock grazing because of species composition. Although our sample indicates that 59 percent of the undergrowth consists of vegetation in the desirable and intermediate forage suitability classes, this can be misleading when applied to all stands within the type. *Veratrum californicum* has the potential to exclusively dominate the undergrowth on some sites. When this occurs, the undergrowth has little value as livestock forage. Lack of structural and species diversity limits the value of this type as wildlife habitat.

Although scarce, this type is fairly widespread. Hoffman and Alexander (1980) described a *P. tremuloides/Veratrum tenuipetalum* habitat type on the Routt National Forest in northwestern Colorado, which is also restricted to wet sites. According to Harrington (1954), *V. tenuipetalum* and *V. californicum* are synonymous.

Populus tremuloides/Heracleum lanatum Community Type (POTR/HELA c.t.)

Although not encountered frequently, representatives of the POTR/HELA c.t. were found from the Bear River Range in extreme northern Utah southward to the Fishlake Plateau in central Utah. We sampled 14 stands that generally occupied fairly shallow slopes on northerly and easterly exposures. The type was primarily on soils derived from sandstone, but it also occurred on limestone, quartzite, and volcanics. Elevations ranged from approximately 7,000 to 9,300 ft (2 130 to 2 830 m). These sites were fairly moist but not as moist as those occupied by the POTR/VECA c.t.

The vegetation in this type consists of only two distinct strata: the aspen overstory and a diverse herbaceous undergrowth. Occasional shrubs, primarily *Symphoricarpos oreophilus* and *Sambucus racemosa*, may be present but are never abundant. The undergrowth usually is dominated by a mixture of tall-growing forbs of which *Heracleum lanatum* is a conspicuous constant and usually abundant typifying species (fig. 5). Other forbs frequently prominent in this type include *Rudbeckia occidentalis*, *Senecio serra*, *Polemonium foliosissimum*, *Mertensia arizonica*, *Valeriana occidentalis*, and *Delphinium occidentale*. Frequent and sometimes abundant grasses include *Bromus carinatus* and *Elymus glaucus*.

This appears to represent a fairly moist, climax community type. Many of the tall forbs found in the type, and especially *H. lanatum*, are palatable to both sheep and cattle. Abusive grazing by either class of livestock probably will result in a decrease of *H. lanatum* and other palatable forbs with an accompanying increase in *R. occidentalis*, *Vicia americana*, *Lathyrus* spp., and possibly *S. serra*. Continued abuse would tend to eliminate the palatable perennials and encourage occupancy by such annuals as *Nemophila breviflora* and *Galium bifolium*.

Tree productivity on this relatively moist site varies widely but is usually high. Basal area ranged from 87 to 283 ft^2/acre (19.9 to 65.1 m^2/ha), and averaged 183 ft^2/acre (42 m^2/ha). This consisted almost entirely of aspen. Site index for aspen at 80 years ranged from 45 to 78 ft (13.7 to 23.8 m) and averaged 65 ft (19.9 m). Aspen reproduction within these mature stands varied widely but was generally high, averaging almost 5,600 suckers/acre (13 900/ha), three-fourths of which were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Undergrowth production generally is high and dominated by forbs, many of which are palatable to livestock. Production ranged from 956 to 1,692 lb/acre (1 083 to 1 899 kg/ha) and averaged 1,228 lb/acre (1 378 kg/ha). Over three-fourths of this production consisted of forbs and the remainder was divided between graminoids and shrubs. Of the undergrowth, 85 percent fell into the desirable and intermediate forage suitability classes. The type is considered good summer range for livestock, particularly for sheep, but of only moderate value as wildlife habitat because of relatively low structural diversity.

Figure 5.—The infrequent but broad-ranging *Populus tremuloides/Heracleum lanatum* c.t. is structurally simple but is usually productive. *Heracleum lanatum* is a conspicuous component of the undergrowth. This stand occupies a moist, easterly exposure at 8,000 ft (2 440 m) elevation near Mt. Timpanogos on the Uinta National Forest; 98 percent of the undergrowth production was forbs.

Types similar to the POTR/HELA c.t. occur at least in Wyoming and in Colorado. Youngblood and Mueggler (1981) describe such a type in western Wyoming that is virtually identical. A *P. tremuloides/Heracleum sphondylium* habitat type was described for northwestern Colorado (Hoffman and Alexander 1980, 1983) that is similar to our type. Dorn (1977) indicates that *H. sphondylium* is synonymous with *H. lanatum*.

Populus tremuloides/Pteridium aquilinum Community Type (POTR/PTAQ c.t.)

This infrequent but distinct community type occurred principally on the Wasatch Range in northern Utah, particularly on that portion between Salt Lake City and Heber City. One stand was encountered as far south as the Markagunt Plateau east of Cedar City. The 13 stands sampled within this type generally ranged in elevation between 5,800 and 8,400 ft (1 770 and 2 560 m). The stand in southern Utah was at 9,350 ft (2 850 m). These stands occupied soils of sedimentary as well as granitic origin. They did not appear restricted by either exposure or steepness of slope.

The POTR/PTAQ c.t. is readily identified by the abundance of *Pteridium aquilinum* in the undergrowth and the absence of a pronounced shrub stratum (fig. 6). However, minor amounts of some shrubs, particularly *Symphoricarpos oreophilus* and *Sambucus racemosa*, may be present. Members of the tall forb group are usually associated in the herbaceous layer with the conspicuously dominant *P. aquilinum*. The most frequent of these are *Rudbeckia occidentalis, Agastache urticifolia, Senecio serra*, and *Aster engelmannii*. Occasionally *Lathyrus* spp. may be abundant. Graminoids, especially *Bromus carinatus* and *Elymus glaucus*, are often present in substantial amounts. Conifers are usually absent.

The successional status of this type is uncertain. *Pteridium aquilinum* is a native species sporadically distributed in Utah and elsewhere throughout the West. Where it does occur, however, it is usually a dominant

Figure 6.—The distinctive *Populus tremuloides/ Pteridium aquilinum* c.t., though seldom encountered, is widespread in the Intermountain and Rocky Mountain area. *Pteridium aquilinum* overwhelmingly dominates the undergrowth in this stand found in the Big Flat area of the Uinta National Forest west of Heber City.

part of the undergrowth. This suggests that it may be indicative of a specific site situation, and that such stands represent more or less stable conditions or climax community types. On the other hand, *P. aquilinum* is both unpalatable to livestock and reproduces readily by creeping rhizomes. Overgrazing that inhibits the growth of palatable forage species would encourage the growth and reproduction of *P. aquilinum*. Judging from undergrowth composition, this type might also represent a grazing-degraded seral stage of a POTR/SESE climax community type, if the presence of *P. aquilinum* were ignored. In either event, abusive grazing will tend to encourage dominance of *P. aquilinum* and possibly *R. occidentalis* at the expense of such forage species as *A. engelmannii, A. urticifolia, B. carinatus*, and *E. glaucus*.

Tree production within this type is moderate to high. Basal area, 99 percent of which was aspen, ranged from 76 to 224 ft^2/acre (17.3 to 51.4 m^2/ha) and averaged a moderate 146 ft^2/acre (33.6 m^2/ha). Aspen site index at 80 years ranged from 47 to 78 ft (14.3 to 23.8 m) and averaged a moderately high 60 ft (18.3 m). Aspen reproduction varied widely but was comparatively high for mature stands. It averaged approximately 7,600 suckers/acre (18 900 ha), of which about half were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Although undergrowth production in this type is generally high, it is of low to moderate value as livestock forage. Production ranged from 1,035 to 2,292 lb/acre (1 162 to 2 572 kg/ha) and averaged 1,570 lb/acre (1 762 kg/ha). Over 90 percent of this was forbs, primarily the unpalatable *P. aquilinum*. Of the total undergrowth, 48 percent was classified within the least desirable forage suitability class. The type also has low to moderate value as wildlife habitat because it lacks structural diversity as well as having a low abundance of palatable species.

Although infrequent, the POTR/PTAQ type appears fairly widespread. Hoffman and Alexander (1980, 1983) identified similar aspen stands with *P. aquilinum* dominating the undergrowth as a distinct habitat type on the Routt and White River National Forests in northwestern Colorado. The main difference in the Colorado communities is the occurrence of substantial amounts of *Carex geyeri* in most stands.

Populus tremuloides/Senecio serra Community Type (POTR/SESE c.t.)

The POTR/SESE community type is one of the most frequently encountered types in northern Utah. We sampled 125 stands to form the data base for this type. Although the type occurs principally on the Bear River and Wasatch Ranges and on the west slope of the Uintas, it can be found at scattered locations throughout the higher elevations as far south as the Abajo Mountains in the southeast and the Markagunt Plateau in southwestern Utah. It is primarily a middle to fairly high elevation type; sampled stands ranged in elevation between 6,000 to 10,300 ft (1 830 and 3 140 m). These stands occurred on all exposures, mostly on gentle to moderately steep slopes, and on relatively deep soils derived from sandstone, limestone, quartzite, and granitic parent materials. Stands were seldom found on volcanic soils.

Vegetation in this common type is structurally simple but compositionally complex. An occasional conifer, usually *Abies lasiocarpa*, may be present with the aspen but in only small amounts. A shrub stratum per se is lacking even though *Symphoricarpos oreophilus* and *Sambucus racemosa* are often present as incidental species. Consequently, the aspen undergrowth consists almost exclusively of a broad assemblage of herbaceous species characterized by a diverse mixture of tall forbs, no one of which is consistently dominant, accompanied by low forbs, graminoids, and annuals (fig. 7). Although *Senecio serra* is used as an epithet representing the tall forb group, it need not be present for a stand to qualify for this community type. Species of tall forbs commonly encountered include *S. serra, Rudbeckia occidentalis,*

Figure 7.—The *Populus tremuloides/Senecio serra* c.t. is one of the most common aspen types, especially in northern Utah. This stand occurred at 8,600 ft (2 620 m) elevation in the upper Cottonwood Creek drainage on the Manti-LaSal National Forest northeast of Fairview. The undergrowth typically consists of a diverse and productive mixture of tall forbs, low forbs, and graminoids.

Valeriana occidentalis, Mertensia arizonica, Agastache urticifolia, Delphinium occidentale, and *Polemonium foliosissimum.* Combinations of these occur in varying but usually noticeable amounts. Other common forbs include *Thalictrum fendleri, Stellaria jamesiana, Osmorhiza chilensis, Vicia americana,* and *Lathyrus* spp. Substantial amounts of grasses are usually interspersed among the forbs; most common and abundant of these are *Bromus carinatus, Agropyron trachycaulum,* and *Elymus glaucus.* Pocket gophers frequently churn the relatively deep, loose soil of this type, providing conditions amply suited for the growth of such annuals as *Nemophila breviflora, Polygonum douglasii, Collomia linearis,* and *Galium bifolium.*

POTR/SESE is a major climax aspen community type that is especially prevalent in northern Utah. Occasional stands classified into this type could be considered seral communities within the *A. lasiocarpa/O. chilensis* habitat type (Mauk and Henderson 1984) if *A. lasiocarpa* were able to actively invade and replace the aspen overstory. Prolonged heavy grazing in this type will probably cause a substantial reduction in species diversity. If abusively grazed by sheep, a decrease in the more palatable forbs can be expected with a corresponding increase in *E. glaucus, B. carinatus,* and *R. occidentalis.* Such use by cattle will tend to shift community composition strongly toward *R. occidentalis* and possibly *Lathyrus* spp. In some cases, *S. serra* may also increase substantially under heavy cattle use. Prolonged abusive grazing by either class of livestock would likely eliminate many of the more palatable perennials and favor an increase in annuals (fig. 8).

The potential of the type for wood production appears to be slightly better than the average for all of the aspen community types. We sampled 64 stands within this type for production. Tree basal area ranged from 46 to 302 ft^2/acre (10.7 to 69.4 m^2/ha) and averaged 152 ft^2/acre (35.0 m^2/ha). An average 99 percent of this was aspen. Site index at 80 years for aspen ranged widely from 32 to 85 ft (9.8 to 25.9 m), and averaged a moderate 54 ft (16.5 m). Aspen reproduction also varied greatly. Sucker numbers ranged between none to well over 8,100/acre (20 000/ha), and averaged slightly over a moderate 2,500/acre (6 100/ha). Approximately half of these suckers were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Undergrowth production in this extensive type varies greatly but overall appears to be about average for all aspen types. Based on a sample of 59 stands, it ranged from 234 to 2,853 lb/acre (263 to 3 202 kg/ha) and averaged 1,149 lb/acre (1 289 kg/ha). The bulk of this undergrowth, 72 percent, consisted of forbs; graminoids comprised 25 percent, and shrubs 3 percent. Of the vegetation, 79 percent was classified as either desirable or of intermediate forage suitability. The type, therefore, is at least moderately productive livestock range, particularly for sheep. Shrub cover usually is incidental; structural diversity is therefore low even though species diversity may be high. Thus, the type is only of relatively moderate value as wildlife habitat because of the absence of an effective shrub component in the undergrowth.

Not only is the POTR/SESE c.t. common in Utah, aspen communities with similar vegetation structure and characterizing species are widespread elsewhere. The *P. tremuloides/R. occidentalis* community type described for the Caribou and Targhee National Forests in Idaho (Mueggler and Campbell 1982) apparently is a generalized combination of stands that fall within our POTR/SESE c.t. and POTR/HELA c.t. Those stands similar to our POTR/SESE type have many of the same characteristics but lack the *Lathyrus* spp. and *Vicia americana* that are common in the Utah stands. Both the *P. tremuloides/R. occidentalis* and *P. tremuloides/ Ligusticum filicinum* types described by Youngblood and Mueggler (1981) for western Wyoming contain stands similar to our POTR/SESE c.t. except for the lack of *Lathyrus* spp. and *V. americana* in the Wyoming stands and the greatly reduced occurrence of *L. filicinum* in the Utah stands. About half the aspen stands Hoffman and Alexander (1980, 1983) used to characterize the *P. tremuloides/T. fendleri* habitat type in northwestern

Figure 8.—Prolonged abusive grazing can reduce the productive undergrowth of the *Populus tremuloides/ Senecio serra* c.t. (fig. 7) to an impoverished condition dominated by such annuals as *Nemophila breviflora, Collomia linearis, Polygonum douglasii,* and *Galium biflorum,* with only trace amounts of the former perennial cover. An example is this stand on the Nebo Loop Road, Uinta National Forest.

Colorado contain the tall forb and grass components similar to our POTR/SESE c.t. Their *P. tremuloides/T. fendleri* type appears to be primarily a more generalized combination of our POTR/SESE and POTR/CAGE types. Aspen communities similar to the Utah POTR/SESE c.t. have also been noted in northeastern Nevada (Lewis 1975).

Populus tremuloides/Carex geyeri Community Type (POTR/CAGE c.t.)

This is a relatively common community type widely distributed in the higher mountains throughout Utah, with 90 percent of the 49 sampled stands at elevations over 8,000 ft (2 440 m). The type was found on all exposures, on shallow to steep slopes, and on a wide variety of soil parent materials. The type occurred most frequently on soils derived from sandstone, volcanics, and granite.

The vegetation of this type bears considerable resemblance to that of the POTR/SYOR/CAGE community types except for the lesser amounts of the key shrubs. *Symphoricarpos oreophilus* or *Juniperus communis* or both are frequently part of the undergrowth in the POTR/CAGE c.t., but not in such amounts that form a distinct shrub stratum. Vegetation structure, therefore, consists essentially of only two layers: the *Populus tremuloides* dominated overstory and the herbaceous undergrowth (fig. 9). *Abies lasiocarpa* and *Picea engelmannii* occasionally accompany *P. tremuloides* in the tree layer but only as incidental species. *Berberis repens* at times provides considerable ground cover. The undergrowth typically consists of substantial amounts of one or more of the following graminoids: *Carex geyeri, Carex rossii, Stipa occidentalis*, and *Calamagrostis rubescens*. These species are considered more or less ecological equivalents in this classification (see the POTR/SYOR/CAGE c.t. section). *Carex geyeri* and *C. rubescens* are most frequently encountered in northern Utah, whereas *S. occidentalis* and *C. rossii* appear more widely distributed. Frequently *Agropyron trachycaulum* is also abundant. The most common forbs in this community type are *Achillea millefolium, Astragalus miser, Geranium viscosissimum*, and *Taraxacum officinale*. Considerable amounts of *Lathyrus* spp. may also be present in some stands.

We believe that the POTR/CAGE is primarily a climax community type. In those cases where *A. lasiocarpa* appears able to actively invade and replace *P. tremuloides*, the stand might be considered a seral stage within an *A. lasiocarpa/B. repens* habitat type (Mauk and Henderson 1984). Heavy, prolonged grazing of this type will probably shift undergrowth composition toward greater abundance of *A. miser, T. officinale*, and *Poa pratensis* as the less grazing-tolerant forage species are reduced.

Although tree basal area is relatively high in this type, growth rate is only moderate. Tree basal area on the 24 stands sampled for production ranged from 89 to 322 ft^2/acre (20.5 to 73.9 m^2/ha) and averaged 171 ft^2/acre (39.2 m^2/ha). Aspen constituted 99 percent of this. Site index of aspen at 80 years ranged from 32 to 77 ft (9.8 to 23.5 m) and averaged a modest 52 ft (15.7 m). Aspen reproduction averaged a moderate 2,200 suckers/acre (5 500/ha) about half of these in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Annual production of undergrowth usually is fairly low. Although it ranged from 78 to 1,289 lb/acre (88 to 1 447 kg/ha) across 23 stands, it averaged a rather meager 665 lb/acre (746 kg/ha). This production was about equally divided between forbs and graminoids, with less than 5 percent in the shrub category. Of the undergrowth, 93 percent was classified in the desirable and intermediate forage suitability classes. The high percentage of graminoids makes this type better suited for cattle than for sheep. Low productivity, however, limits its value as livestock range. The type is not good wildlife habitat because of its lack of diversity in both vegetation structure and species composition.

This relatively common Utah type occurs also in Idaho, Wyoming, and Colorado. Mueggler and Campbell (1982) identified a *P. tremuloides/C. rubescens* c.t. in

Figure 9.—The *Populus tremuloides/Carex geyeri* c.t., widely distributed throughout the higher mountains and plateaus of Utah, has a relatively simple undergrowth dominated by such graminoids as *C. geyeri, Carex rossii*, or *Stipa occidentalis*. Common forbs include *Achillea millifolium, Geranium viscosissimum*, and *Astragalus miser*.

southeastern Idaho that is virtually identical compositionally to our POTR/CAGE c.t. A *P. tremuloides/C. rubescens* type was also identified for western Wyoming (Youngblood and Mueggler 1981) that resembles the Utah type but has more structural variation. *Calamagrostis rubescens* usually replaces *C. geyeri* as the characterizing graminoid in these more northern locations. In northwestern Colorado, a structurally and compositionally similar type was identified by Hoffman and Alexander (1983) as the *P. tremuloides/C. geyeri* habitat type. Although the *P. tremuloides/C. geyeri* habitat type described by Wirsing and Alexander (1975) for southeastern Wyoming contains the same characterizing graminoids in the herbaceous stratum, it differs structurally from our POTR/CAGE c.t. because of the abundance of the shrub *J. communis*; their type corresponds more closely to our POTR/JUCO/CAGE c.t.

Populus tremuloides/Festuca thurberi Community Type (POTR/FETH c.t.)

This infrequent community type was encountered only in the southern portion of Utah on the Fishlake, Sevier, and Aquarius Plateaus. The 14 sampled stands were at elevations ranging from 8,000 to 9,500 ft (2 440 to 2 900 m), on moderately steep concave or undulating slopes and over a wide variety of exposures. The stands were encountered only on soils derived from volcanic or granitic parent materials.

The vegetation is characterized by an abundance of the tussock *Festuca thurberi* in the undergrowth (fig. 10). The type is differentiated from the POTR/SYOR/FETH c.t. by the lack of a distinct *Symphoricarpos oreophilus*-dominated shrub layer. However, *S. oreophilus* is frequently present but only in minor amounts. The overstory consists of *Populus tremuloides* with an occasional conifer, primarily *Abies lasiocarpa* and *Picea engelmannii*. Usually *Stipa occidentalis* is present; occasionally *Bromus carinatus* is abundant. The most common forbs associated with these grasses are *Taraxacum officinale, Achillea millefolium, Vicia americana*, and *Lathyrus* spp. In some cases, *Lathyrus* spp. appears to dominate the undergrowth.

The POTR/FETH is basically a climax community type. However, many of the stands in this type appear to have undergone considerable grazing pressure in the past, judging from the amount of *T. officinale, Lathyrus* spp., and *Poa pratensis*. Possibly these stands have had appreciably more *S. oreophilus* that may have been reduced to present levels by heavy sheep use. Such stands would be considered seral stages of a climax POTR/SYOR/FETH c.t. Heavy sheep use would support the increase of *A. millefolium, T. officinale*, and *P. pratensis; F. thurberi* probably would not be adversely affected unless such use were extreme. Heavy cattle use would tend to reduce the *F. thurberi* and support an increase in the remaining forbs and *P. pratensis*.

This type is productive for aspen. Basal area of the five stands sampled for production ranged from 134 to 325 ft^2/acre (30.8 to 74.6 m^2/ha) and averaged a high 199 ft^2/acre (45.6 m^2/ha). Virtually all of this basal area consisted of aspen. Site index at 80 years for aspen ranged from 53 to 63 ft (16.2 to 19.2 m) and averaged a moderately high 59 ft (17.9 m). Aspen reproduction was generally low, averaging approximately 1,000 suckers/acre (2 500/ha). Two-thirds of these were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Annual production of undergrowth varies widely but is generally moderate. It averaged 1,218 lb/acre (1 367 kg/ha) on the sampled stands but ranged from 448 to 3,492 lb/acre (502 to 3 919 kg/ha). This consisted of 58 percent graminoids and 41 percent forbs. A total of 89 percent was classified as either desirable or as intermediate forage suitability. Considering total productivity and the high proportion of grasses, the type is fairly good livestock range, especially for cattle. Lack of a shrub complex, which contributes to structural diversity, limits the type's value as wildlife habitat.

Aspen communities with *F. thurberi* prominent in the undergrowth have also been reported in Colorado. Langenheim (1962) described stands in the Crested Butte area in west-central Colorado that lacked a promi-

Figure 10.—The *Populus tremuloides/Festuca thurberi* c.t. is an uncommon but distinct type found in southern Utah. This stand in the upper Um Creek drainage on the Fishlake National Forest produced an unusually great amount of undergrowth, 3,492 lb/acre (3 919 kg/ha), of which almost three-fourths was *F. thurberi*.

nent shrub layer. Although the undergrowth was dominated by *Thalictrum fendleri, Ligusticum porteri*, and *V. americana*, those stands contained appreciable amounts of *F. thurberi*.

Populus tremuloides/Sitanion hystrix Community Type (POTR/SIHY c.t.)

The POTR/SIHY c.t. is a fairly uncommon and relatively arid type found primarily in southern Utah. It was usually encountered on the Aquarius and Markagunt Plateaus. One stand was observed on the south slope of the Uinta Mountains north of Roosevelt. The 11 stands sampled in this type were on widely different exposures, shallow to moderately steep slopes, and on soils derived primarily from volcanic, granitic, or sandstone parent materials. These stands were at elevations between 8,000 and 9,500 ft (2 440 and 2 900 m).

Vegetation structure of this type is essentially two-layered: a *Populus tremuloides* overstory with a rather sparse undergrowth composed largely of graminoids. Although *Juniperus communis, Berberis repens*, and *Symphoricarpos oreophilus* may occasionally be present, they are never abundant enough to form a distinct shrub layer. The herbaceous undergrowth is usually dominated by *Sitanion hystrix, Stipa comata*, and *Poa fendleriana*. The most conspicuous forbs are usually *Antennaria microphylla, Lupinus argenteus*, and *Taraxacum officinale*. This type differs from the POTR/JUCO/SIHY c.t. primarily in the lack of a distinct shrub layer of *J. communis* or *Artemisia tridentata* or both, and by the greater abundance of *S. hystrix* and *S. comata*.

This appears to be a relatively stable aspen type restricted to comparatively dry sites. *Pinus ponderosa* may be present occasionally as an accidental species. In stands where *P. ponderosa* is actively invading, and especially if *J. communis* is also present, the stands probably should be placed in the POTR-PIPO/JUCO c.t.

The abundance of *S. hystrix* and *T. officinale* suggests that the undergrowth has been appreciably degraded by prolonged and heavy livestock grazing. Very likely *P. fendleriana, Bromus ciliatus*, and possibly *S. oreophilus* were more abundant in many of these stands prior to the advent of domestic livestock. Continued abusive grazing would favor an even greater abundance of such low-palatability species as *S. hystrix* and *A. microphylla*, and a loss of those species that are more palatable to sheep and cattle.

The type is only moderately productive for trees. Basal area ranged from 94 to 203 ft^2/acre (21.5 to 46.6 m^2/ha) but averaged only 155 ft^2/acre (35.7 m^2/ha). Aspen made up 96 percent of this total. Aspen site index at 80 years ranged from 30 to 63 ft (9.1 to 19.2 m) and averaged a moderately low 47 ft (14.3 m). Aspen reproduction was also low with suckers averaging less than 770/acre (1 900/ha), two-thirds of which were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Undergrowth production is generally low and rather evenly divided between forbs and grasses. Annual production ranged from 319 to 823 lb/acre (358 to 923 kg/ha) and averaged only 472 lb/acre (530 kg/ha). Graminoids made up 47 percent of this, 51 percent was forbs, and only 2 percent was in the shrub category. However, 62 percent of the undergrowth was desirable forage and 33 percent was of intermediate suitability. Although the type does not support much undergrowth, it does rate high as livestock forage, especially for cattle. This relatively dry type is rather poor wildlife habitat because the vegetation lacks good structural diversity and produces comparatively little undergrowth.

Aspen communities resembling this type have not been reported outside of Utah.

Populus tremuloides/Bromus carinatus Community Type (POTR/BRCA c.t.)

This seral community type was encountered primarily in northern and central Utah, but one stand was observed in the Abajo Mountains in the southeast corner of the State. The type is somewhat infrequent. We sampled only 14 stands occurring at elevations between 7,400 and 9,400 ft (2 260 and 2 870 m) on usually less than 25-percent slopes and on all exposures. The type occurs primarily on sedimentary soils derived from sandstone and limestone parent materials.

Conifers are seldom present and never abundant in the POTR/BRCA c.t. The undergrowth vegetation is typified by the lack of a shrub layer and the dominance of tall grasses, *Bromus carinatus* or *Elymus glaucus* or both in the herbaceous layer (fig. ll). Shrubs, especially *Symphoricarpos oreophilus*, are often present but never in such amounts to form a distinct stratum. Principal forbs most frequently present are *Thalictrum fendleri, Achillea millefolium, Rudbeckia occidentalis, Vicia americana*, and *Lathyrus* spp. This type is similar to the POTR/SYOR/BRCA c.t., except for the lack of shrubs.

Although the aspen overstory apparently is stable in the POTR/BRCA c.t., the undergrowth is considerably altered by grazing. The type is most likely seral to the POTR/SESE climax community type. Heavy and prolonged sheep use appear to have reduced the abundance of tall forbs and permitted substantial increases in the amount of *B. carinatus, E. glaucus*, and *Agropyron trachycaulum*. The type is similar to the POTR/SYOR/BRCA c.t., except for a lesser amount of *S. oreophilus* and *Geranium viscosissimum*, both of which tend to decrease with heavy sheep use. Thus, it is possible that the POTR/BRCA c.t. may also be a grazing-induced seral stage of the POTR/SYOR/SESE climax community type. Heavy grazing of the POTR/BRCA c.t. by cattle would tend to result in a decrease of *B. carinatus, A. trachycaulum*, and *E. glaucus*, and an increase of *R. occidentalis, Poa pratensis*, and *Taraxacum officinale*.

Tree production in this type appears to be only moderately good. Basal area ranged widely between 39 and 189 ft^2/acre (9.0 and 43.4 m^2/ha) and averaged a modest 129 ft^2/acre (29.6 m^2/ha). Virtually all of this was aspen. Site index at 80 years for aspen ranged between 48 and 79 ft (14.6 and 24.1 m) and averaged a moderate 56 ft (17 m). Aspen reproduction was also moderate, averaging less than 1,300 suckers/acre (3 200/ha), about half of which were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Undergrowth production in this grazing-induced type is only moderate. Annual production of dry herbage ranged from 371 to 1,877 lb/acre (417 to 2 106 kg/ha)

Figure 11.—The *Populus tremuloides/Bromus carinatus* c.t. is probably a grazing-induced seral type created by heavy, prolonged sheep grazing of a climax POTR/SESE c.t. The undergrowth in this stand in the upper part of the Seventeen Mile Creek drainage of the Fishlake National Forest is dominated by *B. carinatus* and *Agropyron trachycaulum*.

and averaged 1,219 lb/acre (1 369 kg/ha). The bulk of this was divided rather evenly between grasses (50 percent) and forbs (46 percent); only 4 percent was shrubs. Of the undergrowth, 35 percent was classified as desirable and 60 percent was of intermediate forage suitability. The type, therefore, is moderately productive livestock range, particularly for cattle. Because this type apparently has been altered considerably by heavy grazing, its potential for producing forage is probably greater than its current production. Judging from perceived successional relationships, the proportion of palatable forbs and possibly shrubs was at one time much greater than at present. Wildlife habitat values are comparatively low because of the simplicity of vegetation structure and lack of undergrowth diversity.

This seral type has not been reported elsewhere. But because it is believed to represent a grazing-degraded stage of the POTR/SESE c.t. and possibly the POTR/SYOR/SESE type, which are both present in surrounding States, this seral type likely occurs there as well.

Populus tremuloides/Poa pratensis Community Type (POTR/POPR c.t.)

The POTR/POPR c.t. is a seral type that, although not common, spans the State from the Bear River and Uinta Mountains in the north, to the Markagunt Plateau and LaSal Mountains in the south. We sampled 18 stands to describe this type, ranging in elevation from 7,000 to 9,450 ft (2 130 to 2 880 m) and usually occurring on flats or shallow slopes (less than 25 percent) of northerly or easterly exposures. Soil parent material did not appear restrictive.

The vegetation of this degraded type is relatively simple (fig. 12). It differs from that of the POTR/SYOR/POPR c.t. only in the amount of *Symphoricarpos oreophilus*. Although *S. oreophilus* is usually present in the POTR/POPR c.t., it is never sufficiently abundant to form a distinct shrub layer. The depauperate undergrowth is dominated by *Poa pratensis* or *Taraxacum officinale* or both. Substantial amounts of *Agropyron trachycaulum* are also frequently present. A

Figure 12.—The *Populus tremuloides/Poa pratensis* c.t. is a grazing-induced type dominated by such grazing-resistant species as *P. pratensis, Taraxacum officinale, Achillea millifolium,* and *Trifolium longipes*, as in this stand on Webster Flat southeast of Cedar City. Although not common, the type is encountered occasionally on flats or shallow slopes throughout Utah.

limited variety of other species such as *Berberis repens, Rosa woodsii, Osmorhiza chilensis, Lupinus argenteus, Astragalus miser*, and *Vicia americana* may be irregularly present in lesser amounts.

A variety of conifers may occur in this type as incidentals, but the aspen overstory appears to be stable. The undergrowth, however, reflects a long history of overgrazing of what probably was once either a POTR/CAGE or a POTR/SYOR/CAGE climax community type. The dominant *P. pratensis* and *T. officinale* are palatable to both cattle and sheep. Their growth form enables them to withstand grazing and increase in amount as competition from the more grazing-sensitive species is reduced. Continued heavy grazing probably will not further alter the undergrowth appreciably, at least until the aspen overstory begins to break up with old age and browsing suppresses aspen sucker regeneration. If this should happen, the aspen stand will eventually be lost.

This type is generally only moderately productive for growth of trees. Tree basal area ranged from 71 to 193 ft^2/acre (16.3 to 44.3 m^2/ha) and averaged 126 ft^2/acre (28.9 m^2/ha). All but 1 percent of this was aspen. Site index at 80 years ranged from 30 to 70 ft (9.1 to 21.3 m) and averaged a moderate 53 ft (16.1 m). Aspen regeneration was a moderate 1,900 suckers/acre (4 700/ha). Slightly more than half of these were in the 1- to 4.6-ft (0.3- to 1.4-m) height class.

Forage production on this grazing-altered type generally appears to be considerably less than the potential for the site. Not only has heavy grazing changed undergrowth composition but may have reduced its total biomass as well. Undergrowth production varied from 303 to 1,287 lb/acre (340 to 1 445 kg/ha) and averaged a low to moderate 780 lb/acre (876 kg/ha). This was composed of 58 percent forbs, 37 percent graminoids, and 5 percent shrubs. Only 29 percent of the vegetation was desirable forage; 69 percent was of intermediate forage suitability. This contrasts markedly with 57 percent in the desirable category for the successionally related POTR/CAGE c.t., and 51 percent desirable in the related POTR/SYOR/CAGE c.t. Therefore, the POTR/POPR type should be considered relatively poor livestock range that has considerable potential for improvement. The simplicity of vegetation structure and species composition detracts considerably from the value of this type as wildlife habitat. It and the POTR/SIHY c.t. are probably among the poorest of the aspen types for this use.

A similar *P. tremuloides/P. pratensis* seral type has been identified in southeastern Idaho (Mueggler and Campbell 1982). Although not reported elsewhere, similar communities likely occur in Wyoming and Colorado. The type is probably a grazing-induced seral stage of the POTR/CAGE and POTR/SYOR/CAGE types, which apparently do occur in these states (Hoffman and Alexander 1983).

Populus tremuloides-Abies lasiocarpa/ Vaccinium caespitosum Community Type (POTR-ABLA/VACA c.t.)

This infrequent community type is primarily restricted to the Uinta Mountains. We sampled only four stands at approximately 9,000 ft (2 740 m) elevation on moderately steep slopes with concave or undulating topography. They occupied soils principally derived from quartzite parent materials.

The POTR-ABLA/VACA c.t. is a seral type that is rapidly succeeding to conifers. Both *Abies lasiocarpa* and *Pinus contorta* are replacing *Populus tremuloides* in the overstory. A low shrub layer consisting primarily of either *Vaccinium caespitosum* or *Vaccinium scoparium* dominates the undergrowth. Herbaceous cover is generally sparse, with *Arnica latifolia* usually being most abundant.

Apparently, the type is a seral stage within the *A. lasiocarpa/V. caespitosum* or possibly the *A. lasiocarpa/V. scoparium* habitat types (Mauk and Henderson 1984). *Populus tremuloides* is intolerant of shade and is subject to rapid replacement by *A. lasiocarpa*, barring fire or other disturbance that would retard the conifers. As the conifer cover increases, the undergrowth will become even more depauperate. An aspen stand can only be maintained here by periodic clearcutting, burning, or other disturbance that kills the conifers and stimulates aspen suckering.

Neither tree nor undergrowth productivity were sampled in this type. However, tree basal area, primarily conifers, averaged 170 ft^2/acre (39 m^2/ha) in the successionally related *Abies lasiocarpa/Vaccinium caespitosum* habitat type, and 178 ft^2/acre (41 m^2/ha) in the possibly related *A. lasiocarpa/V. scoparium* habitat type (Mauk and Henderson 1984).

Annual undergrowth production within this seral type depends, to a great extent, upon the amount of conifers present. Typically, as the proportion of conifers increases, undergrowth decreases. The somewhat similar POTR-ABLA/CAGE c.t., with an average 20 percent conifers in the overstory, produced approximately 270 lb/acre (300 kg/ha) undergrowth. Production within the POTR-ABLA/VACA c.t. probably averages about this amount. Judging from species composition of the undergrowth, approximately a third of this is in the desirable and two-thirds is in the intermediate forage suitability class. Thus, the type is poor livestock range and probably not more than moderate wildlife habitat.

This seral type has not been specifically identified as occurring outside of Utah. However, it or a similar seral type may be present at least in northwestern Colorado. Hoffman and Alexander (1980, 1983) indicate that *P. tremuloides* is a seral species in the *A. lasiocarpa/ V. scoparium* habitat type found there.

Populus tremuloides-Abies lasiocarpa/ Amelanchier alnifolia Community Type (POTR-ABLA/AMAL c.t.)

This minor seral community type was encountered principally on the Bear River and Wasatch Ranges in northern Utah. Two stands were observed in the Abajo Mountains of southeastern Utah. The type occurred at the lower edge of the *Abies lasiocarpa* zone. The northern Utah stands were at elevations between 6,300 and 7,800 ft (1 920 and 2 380 m), whereas those in the Abajo Mountains were at 8,600 ft (2 620 m). The type occurred most frequently on slopes with northerly and easterly exposures and occupied soils derived from a wide variety of parent materials.

The POTR-ABLA/AMAL c.t. contains a high degree of both structural and species diversity. The vegetation is comprised of four more or less distinct layers. The tree overstory is dominated by *Populus tremuloides* but has a substantial amount of *A. lasiocarpa* that may also be accompanied by other conifers. The tall shrub layer in the undergrowth is typified by the presence of *Amelanchier alnifolia, Prunus virginiana,* or *Acer grandidentatum.* A pronounced low shrub layer exists that usually has *Symphoricarpos oreophilus* as its most abundant constituent. Other frequently abundant shrubs include *Pachistima myrsinites, Berberis repens,* and *Rosa woodsii.* The herbaceous layer usually contains a rich mixture of graminoids and forbs. *Thalictrum fendleri* is usually among the most abundant and may be accompanied by such species as *Aster engelmannii, Senecio serra, Geranium viscosissimum, Osmorhiza chilensis, Elymus glaucus,* and *Agropyron trachycaulum.*

The type obviously represents a seral stage within the *A. lasiocarpa* coniferous forest series, probably within the *A. lasiocarpa/Acer glabrum* or *A. lasiocarpa/ O. chilensis* habitat types (Mauk and Henderson 1984). The natural process of succession in this type will lead to overstory dominance by *A. lasiocarpa.* As conifers become more prevalent, the shrubby and herbaceous undergrowth tends to become less abundant, less diverse, and shift in composition toward the more shade-tolerant species. Heavy grazing in this type tends to suppress the *S. oreophilus* and *A. engelmannii* and to favor *P. myrsinites* and *B. repens.* If grazed by cattle, composition would additionally tend to shift away from the grasses *A. trachycaulum* and *E. glaucus* and toward a greater abundance of *T. fendleri* and *O. chilensis.* Heavy sheep grazing, on the other hand, would tend to suppress *T. fendleri* and *O. chilensis* and favor the grasses.

Productivity for trees in this seral aspen type appears relatively moderate. Tree basal area ranged from 53 to 288 ft^2/acre (12.1 to 66.2 m^2/ha) and averaged 150 ft^2/acre (34.4 m^2/ha). An average 15 percent of this basal area consisted of conifers and the remainder was aspen. Site index for aspen at 80 years ranged from 47 to 66 ft (14.3 to 20.1 m) and averaged 54 ft (16.5 m). Aspen reproduction averaged approximately 1,800 suckers/acre (4 500/ha), about two-thirds of which were in the large 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer reproduction, 95 percent of which was *A. lasiocarpa,* averaged approximately 890 stems/acre (2 200/ha). About 20 percent of these were in the large size class.

The undergrowth is fairly productive for a seral type and contains a high proportion of shrubs. Annual growth ranged from 578 to 1,986 lb/acre (649 to 2 229 kg/ha) and averaged a moderate 1,256 lb/acre (1 410 kg/ha). An average 53 percent of this was shrubs, 36 percent forbs, and only 11 percent graminoids. A high 62 percent of the undergrowth is of desirable forage suitability. The type is good livestock range, particularly for sheep, if succession has not progressed to the point where conifers are appreciably suppressing the production of shrubs and herbs. The type is considered excellent wildlife habitat because of the great amount of structural diversity: an overstory consisting of both aspen and conifers, a tall shrub layer, a low shrub layer, and an herb layer of forbs and grasses.

This seral type has not been identified elsewhere. However, it is believed to be a seral stage in the *A. lasiocarpa/ O. chilensis* habitat type in Utah, and Steele and others (1983) list *P. tremuloides* as a seral species in the *A. lasiocarpa/O. chilensis* habitat type in eastern Idaho and western Wyoming. The seral type was not recognized per se in that area (Mueggler and Campbell 1982; Youngblood and Mueggler 1981).

Populus tremuloides-Abies lasiocarpa/ Symphoricarpos oreophilus/ Senecio serra Community Type (POTR-ABLA/SYOR/SESE c.t.)

The POTR-ABLA/SYOR/SESE c.t. is fairly common in northern Utah and most prominent on the Bear River and Wasatch Ranges and on the west slope of the Uintas. Elsewhere, it is widely scattered, extending southward to occasional occurrences on the high plateaus and mountain ranges in southern Utah. We sampled 48 stands of this type at elevations ranging from 6,800 to 8,900 ft (2 070 to 2 710 m) in northern Utah and between 8,500 and 9,400 ft (2 590 and 2 870 m) in southern Utah. The type occupies all exposures and slopes of varying steepness but usually on concave or undulating topography. The type occurred most frequently on soils derived from sandstone and limestone parent materials but was not encountered on volcanic soils.

The type is characterized by the presence and projected increasing abundance of *Abies lasiocarpa* in the tree layer, the absence of a distinct tall shrub layer, a low shrub layer dominated by *Symphoricarpos oreophilus* or *Rubus parviflorus,* and the prominence of tall forbs or tall grass species in the herbaceous layer. This herb layer usually consists of a rich composite of forbs and grasses. Members of the tall forb group are conspicuous. Although the particular combination of tall forbs present may vary, the most constant are *Senecio serra, Rudbeckia occidentalis, Agastache urticifolia, Valeriana occidentalis, Aster engelmannii, Mertensia arizonica,* and *Delphinium occidentale.* Other forbs commonly present include *Thalictrum fendleri, Hackelia floribunda, Geranium viscosissimum, Osmorhiza chilensis,* and *Vicia americana.* The tall grasses *Bromus carinatus,*

Elymus glaucus, and *Agropyron trachycaulum* are also frequently present.

The POTR-ABLA/SYOR/SESE c.t. represents a seral stage in the *A. lasiocarpa* coniferous forest climax series, probably within the *A. lasiocarpa/O. chilensis* habitat type (Mauk and Henderson 1984). As *A. lasiocarpa* gains overstory dominance, shading intensity increases, *Populus tremuloides* degenerates and fails to sucker, and the highly productive and diverse undergrowth changes to a less complex and productive assemblage of species. The tall forbs, grasses, and shrubs will decrease in importance, whereas *O. chilensis, T. fendleri*, and *Stellaria jamesiana* will become increasingly prominent.

Heavy grazing in this type usually will lead to a decrease of many of the tall forbs, especially *A. urticifolia, A. engelmannii*, and *S. serra*, and an increase in *R. occidentalis, H. floribunda, S. jamesiana, Achillea millefolium*, and possibly *Lathyrus* spp. Prolonged abusive grazing can lead to a substantial increase in *Poa pratensis* and *Taraxacum officinale*, or even replacement of perennial species with annuals such as *Nemophila breviflora, Polygonum douglasii*, and *Collomia linearis*.

Tree production on these sites is slightly better than average. Basal area ranged from 74 to 249 ft^2/acre (17.0 to 57.3 m^2/ha) and averaged a high-moderate 165 ft^2/acre (38 m^2/ha). Conifers made up 13 percent of this, mostly *A. lasiocarpa*. Aspen site index at 80 years ranged from 33 to 74 ft (10.1 to 22.6 m) and averaged a moderate 54 ft (16.6 m). Aspen regeneration was relatively low in these seral stands, averaging slightly over 800 suckers/acre (2 000/ha), of which about half were in the 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer reproduction averaged approximately 240 stems/acre (600/ha), and 80 percent of this was *A. lasiocarpa*. Slightly less than half were in the large reproduction size class.

Undergrowth, though highly variable, is moderately abundant. Annual production for 13 sampled stands ranged between 202 and 2,121 lb/acre (227 and 2 380 kg/ha) and averaged 1,004 lb/acre (1 127 kg/ha). Shrubs were 23 percent and graminoids 18 percent of this, whereas forbs dominated at 59 percent. The vegetation appeared well suited to livestock, with 54 percent in the desirable forage category. The type consequently is fairly good range for livestock, especially in early successional stages before conifers begin to appreciably reduce undergrowth production. The type is also considered good habitat for wildlife because of the relatively high level of vegetation diversity.

The *P. tremuloides-A. lasiocarpa/S. oreophilus* type described by Mueggler and Campbell (1982) for eastern Idaho contains stands similar to this type. Steele and others (1983) indicate that *P. tremuloides* is a major seral species in the *A. lasiocarpa/O. chilensis* habitat type in eastern Idaho and western Wyoming. Because the POTR-ABLA/SYOR/SESE c.t. is believed to be a seral stage in the *A. lasiocarpa/O. chilensis* habitat type in Utah, it is probably farther north as well.

Populus tremuloides-Abies lasiocarpa/ Symphoricarpos oreophilus/Carex geyeri Community Type (POTR-ABLA/ SYOR/CAGE c.t.)

This infrequent but widespread seral community type was encountered from the Bear River Range in the north to the Aquarius Plateau in the south. Of the 14 sampled stands, we encountered five in the LaSal Mountains. Sampled stands occurred at elevations ranging from 7,500 ft (2 290 m) in northern Utah to 9,600 ft (2 930 m) in the south. These stands were most frequently on shallow slopes of less than 25-percent steepness. They did not appear restricted by either slope exposure or soil parent material.

The vegetation of the POTR-ABLA/SYOR/CAGE c.t. consists of three distinct structural layers: a tree layer of mixed *Populus tremuloides* and conifers, a low shrub layer dominated by *Symphoricarpos oreophilus*, and an herbaceous layer with a high proportion of graminoids. Although *Abies lasiocarpa* is the most common conifer invading the aspen community, *Picea engelmannii* and *Pseudotsuga menziesii* may also be conspicuous. The undergrowth composition of this type is fairly similar to that of the POTR/SYOR/CAGE c.t. The low shrub layer is consistently dominated by *S. oreophilus*, but *Berberis repens* and *Rosa woodsii* may also be prominent in this stratum. The herbaceous layer is usually dominated by grasses and sedges. *Carex geyeri* is the most constant and abundant of these, but *Stipa occidentalis* or *Carex rossii* may occasionally replace *C. geyeri* as the dominant graminoid. The forbs most common to this type are *Thalictrum fendleri* and *Achillea millefolium*. At times, *Lathyrus* spp., *Lupinus argenteus*, or *Astragalus miser* are abundant.

This is a seral community type within the *A. lasiocarpa* coniferous forest series. Most likely it represents a seral stage within either the *A. lasiocarpa/ B. repens* or *A. lasiocarpa/C. geyeri* habitat types (Mauk and Henderson 1984; Youngblood and Mauk 1985). As the aspen overstory is gradually replaced by conifers during the natural course of succession, the abundance of undergrowth vegetation will tend to decrease. Heavy livestock grazing in this type will probably lead to increased abundance of *A. miser, Taraxacum officinale*, and *Poa pratensis* at the expense of those species less able to withstand the effects of heavy use. In some stands a large amount of *Lathyrus* spp. or *Lupinus* spp. may result from heavy cattle grazing.

Tree productivity within the type is low. Basal area ranged from 67 to 144 ft^2/acre (15.5 to 33.0 m^2/ha) and averaged only 109 ft^2/acre (25 m^2/ha). Of this basal area, 17 percent was conifers and the remainder was aspen. Site index at 80 years for aspen was also low, ranging from 30 to 45 ft (9.1 to 13.7 m) and averaging only 38 ft (11.5 m). Aspen reproduction averaged a low 890 suckers/acre (2 200/ha), 75 percent of which were in the large 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer regeneration averaged slightly over 120 stems/acre (300/ha), of which 93 percent were *A. lasiocarpa* and less than 20 percent of these were in the large size class.

The undergrowth generally is no more than moderately productive. It ranged from 437 to 1,079 lb/acre (491 to 1 210 kg/ha) and averaged a low to moderate 777 lb/acre (872 kg/ha). An average 26 percent of this was shrubs, 58 percent was forbs, and 16 percent was graminoids. A relatively high proportion of this vegetation, 55 percent, was desirable forage. Less than 10 percent fell into the least desirable category. This seral type, therefore, is moderately productive livestock range in the earlier stages of succession to conifer dominance. It is only moderately desirable wildlife habitat because of the somewhat limited amount of vegetation diversity.

Although this seral community type has not been specifically named as occurring elsewhere, it probably can be found in adjacent States. The type is considered a seral stage in the development of climax *A. lasiocarpa/B. repens* and *A. lasiocarpa/C. geyeri* climax forests of Utah that also occur in Idaho, Wyoming, and Colorado. Steele and others (1983) list *P. tremuloides* as a major seral tree in the *A. lasiocarpa/B. repens* habitat type of eastern Idaho and western Wyoming. Hoffman and Alexander (1980, 1983) indicate that *P. tremuloides* is a major seral tree in the *A. lasiocarpa/C. geyeri* habitat type of northwestern Colorado.

Populus tremuloides-Abies lasiocarpa/Juniperus communis Community Type (POTR-ABLA/JUCO c.t.)

The POTR-ABLA/JUCO c.t. appears restricted in northern Utah to the Uinta Mountains but is much more widespread farther south where it was encountered on the Fishlake, Paunsagunt, and Markagunt Plateaus and in the Tushar Mountains. We sampled 34 stands in this type that generally occurred in the higher mountains at elevations exceeding 8,000 ft (2 440 m). The type otherwise does not appear restricted by either slope exposure or soil parent material.

The vegetation of this type is characterized by the presence of *Abies lasiocarpa* or *Picea engelmannii* along with *Populus tremuloides* in the overstory or as understory reproduction, the absence of a distinct tall shrub layer, and a low shrub layer dominated by *Juniperus communis*. Other conifers frequently present in lesser amounts include *Pseudotsuga menziesii* and *Pinus flexilis*. No single species characterizes the herbaceous undergrowth, which is generally a mixture of various graminoids and forbs. The most common graminoids found here are *Carex rossii, Stipa occidentalis, Bromus anomalus, Bromus ciliatus*, and *Agropyron trachycaulum*. Commonly encountered forbs include *Achillea millefolium, Fragaria vesca, Astragalus miser*, and *Thalictrum fendleri*.

The type obviously represents a seral stage within the *A. lasiocarpa* forest series, probably in either the *A. lasiocarpa/J. communis* or *A. lasiocarpa/Berberis repens* habitat types (Mauk and Henderson 1984; Youngblood and Mauk 1985), judging from species similarities with these habitat types. As with other such aspen communities that are seral to coniferous forests, dominance by *P. tremuloides* can only be maintained by such extreme disturbance as burning, clearcutting, or selective removal of the conifers that would set back the successional processes. Heavy livestock grazing within this type would tend to change the herbaceous composition to favor *A. miser, F. vesca, Taraxacum officinale*, and *Poa pratensis*. The abundance of shrubby *J. communis* undergrowth would likely increase as well.

Tree productivity within this type is at least moderately good. Basal area on the 12 stands sampled for productivity ranged from 98 to 263 ft^2/acre (22.5 to 60.4 m^2/ha) and averaged 166 ft^2/acre (38.1 m^2/ha). Only 10 percent of this was conifers and the rest was aspen. Site index for aspen at 80 years ranged from 32 to 71 ft (9.8 to 21.6 m) and averaged a moderate 52 ft (15.7 m). Aspen reproduction averaged a low 730 suckers/acre (1 800/ha), two-thirds of which were in the 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer reproduction averaged slightly less than 325 stems/acre (800/ha), of which three-fourths were *A. lasiocarpa*, and a third of which were in the large reproduction size class.

Undergrowth production appears to be generally low, ranging between 78 and 1,139 lb/acre (88 and 1 278 kg/ha) and averaging a low 374 lb/acre (420 kg/ha). This was about equally distributed among shrubs, forbs, and graminoids. The undergrowth is considered moderately suitable for livestock with 45 percent of the vegetation in the desirable category. However, generally low production limits the value of this type as livestock range. The type is also of only moderate value as wildlife habitat because neither vegetation structure nor plant species diversity are great.

No one has reported this seral community type to occur outside of Utah.

Populus tremuloides-Abies lasiocarpa/Senecio serra Community Type (POTR-ABLA/SESE c.t.)

This is one of the more common seral community types found throughout the higher mountains of Utah. It is most frequently encountered in northern Utah along the Bear River and Wasatch Ranges and along the west slope of the Uinta Mountains. Of all sampled stands, 8 percent occurred in this community type. Although the type was encountered at elevations as low as 6,400 ft (1 950 m), over two-thirds of the stands were found at elevations between 8,000 and 10,000 ft (2 440 and 3 050 m). The type occupied a wide variety of slopes, exposures, and soils derived from different parent materials.

Vegetation of the POTR-ABLA/SESE c.t. is similar to that of the POTR/SESE type, except for the prominence of conifers in the former. Both types are structurally simple with only a tree overstory and a predominantly herbaceous undergrowth. Shrubs, especially *Symphoricarpos oreophilus*, may occasionally be present but never in sufficient abundance to form a distinct layer. In addition to the paucity of shrubs, the undergrowth is characterized by the conspicuous presence of one or more members of the tall forb complex, usually either *Rudbeckia occidentalis, Senecio serra, Aster engelmannii, Mertensia arizonica*, or *Valeriana occidentalis*. Tall grasses that are in abundance are

Figure 13.—The *Populus tremuloides-Abies lasiocarpa/Senecio serra* c.t. is a seral aspen type common throughout the higher mountains of Utah. The aspen will eventually be replaced by *A. lasiocarpa*. The undergrowth of this stand, on a north exposure in Logan Canyon, Wasatch-Cache National Forest, consists of a mixture of tall and low forbs and graminoids in addition to the conifer reproduction.

Bromus carinatus, Elymus glaucus, or both (fig. 13). Other forbs often conspicuous in this type are *Thalictrum fendleri, Osmorhiza chilensis, Achillea millefolium*, and *Lathyrus* spp.

The aspen overstory in this seral type will eventually be replaced by *A. lasiocarpa* during the natural course of succession. The type is most likely a seral stage in the northern Utah *A. lasiocarpa/O. chilensis* habitat type (Mauk and Henderson 1984) and also probably in the central and southern Utah *A. lasiocarpa/Aconitum columbianum* habitat type (Youngblood and Mauk 1985). As *A. lasiocarpa* gains increasing prominence and *P. tremuloides* decreases in the tree overstory, increased shading will appreciably alter undergrowth production and composition. The tall forb and grass complex will tend to decline whereas such low forbs as *T. fendleri* and *O. chilensis* will gain importance as undergrowth. An aspen-dominated community can be maintained on these sites only if the conifers are removed, usually by such drastic means as burning or clearcutting. When this occurs, *P. tremuloides* rapidly suckers, usually profusely, from the remnant root system, whereas the conifers can only reestablish from seed. Rapidity of aspen replacement by conifers depends to a great extent on the availability of a conifer seed source. Replacement might take place in less than 100 years if abundant conifer seedlings become established from residual seed immediately following the disturbance. In other cases, aspen replacement may not occur for several hundred years if conifer establishment depends upon gradual invasion from outside the stand.

Heavy sheep grazing in this type usually leads to a decrease of many of the palatable tall forbs and an increase in the abundance of the grasses *B. carinatus, E. glaucus*, and *Agropyron trachycaulum*. Under heavy cattle use, the grasses and such palatable forbs as *A. engelmannii, S. serra*, and *M. arizonica* tend to decrease and species such as *R. occidentalis, T. fendleri, A. millefolium*, and *Lathyrus* spp. become more prominent. If consistently grazed only in the latter part of the growing season, *S. serra* and *M. arizonica* may increase substantially. Prolonged abusive grazing could lead to undergrowth dominated by *Taraxacum officinale* and *Poa pratensis*, or eventually replacement of perennial herbs by such annuals as *Nemophila breviflora, Collomia linearis*, and *Galium bifolium*.

Productivity of this type for trees is at least moderately high. Basal area on 49 stands sampled for production ranged from 89 to 351 ft^2/acre (20.4 to 80.6 m^2/ha) and averaged from 177 ft^2/acre (40.7 m^2/ha). An average 23 percent of this basal area was conifers, primarily *A. lasiocarpa*, and the remainder was aspen. Site index for aspen at 80 years ranged from 33 to 74 ft (10.1 to 22.6 m) and averaged a moderate 52 ft (15.8 m). Aspen reproduction averaged approximately 1,300 suckers/acre (3 300/ha). Half of these were in the large 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer reproduction averaged a little over 890 stems/acre (2 200/ha), of which 96 percent was *A. lasiocarpa*. About a third of the stems were in the large size class.

Production of undergrowth in this seral type is greatly reduced as conifers increase in abundance. Undergrowth in the intensively sampled stands ranged widely from 69 to 2,289 lb/acre (78 to 2 568 kg/ha) and averaged only 767 lb/acre (861 kg/ha). An average 69 percent of this was forbs, 28 percent graminoids, and only 3 percent shrubs. An abundant 55 percent of the undergrowth consisted of desirable forage. Only 11 percent was in the least desirable category. The type, therefore, appears to be fairly good livestock range during that time prior to when conifer competition begins to seriously reduce production of the herbaceous undergrowth. Harper (1973) observed that when conifers increased to approximately 20 ft^2/acre (4.6 m^2/ha) in an aspen stand, undergrowth production was cut in half. Therefore, by the time conifer invasion accounts for 10 percent of the tree basal area, undergrowth production is probably being reduced appreciably. The mixture of conifers and aspen contributes to vegetation diversity, but the lack of a shrub stratum detracts from the type's value as wildlife

habitat. Early successional stages are of intermediate value to wildlife. This value decreases as succession proceeds to conifer dominance.

Although not identified by the same name, communities similar to this seral type can also be found in Idaho and adjacent Wyoming. Some of the stands used to describe the *P. tremuloides-A. lasiocarpa/Thalictrum fendleri* type in southeastern Idaho (Mueggler and Campbell 1982) resemble those in our Utah type, except for fewer tall forbs. In Utah, the type is regarded as a successional stage within the *A. lasiocarpa/Osmorhiza chilensis* habitat type. Steele and others (1983) show *P. tremuloides* as a major seral tree in this habitat type in eastern Idaho and western Wyoming.

Populus tremuloides-Abies lasiocarpa/ Carex geyeri Community Type (POTR-ABLA/CAGE c.t.)

This community type is fairly common on the high plateaus and mountains of central and southern Utah, although it is found occasionally in northern Utah, principally in the Uinta Mountains. It is a relatively high elevation type. Over 80 percent of the 77 stands sampled were at elevations over 9,000 ft (2 740 m). These stands most frequently occupied rather gentle slopes, and exposures of the slopes did not appear important. Over three-fourths of the stands occurred on soils derived from either volcanic or granitic parent material.

The conspicuous presence of *Abies lasiocarpa* in the tree stratum clearly reflects this type's successional status. *Picea engelmannii* is also frequently present in the tree layer. The undergrowth is characterized by the absence of a distinct shrub layer and the lack of minimal representation by the tall forb and tall grass group of species. The shrubs *Juniperus communis, Berberis repens*, and *Symphoricarpos oreophilus* occasionally may be present but are never abundant. Consequently the undergrowth consists primarily of low herbaceous growth. This usually is composed of such graminoids as *Carex rossii, Stipa occidentalis*, and *Carex geyeri*, and such forbs as *Fragaria vesca, Astragalus miser, Achillea millefolium*, and *Trifolium longipes*. Even though *C. geyeri* has low constancy, it is used in the type name to reflect this particular herbaceous complex for nomenclature consistency. This undergrowth is similar to that in the POTR/CAGE c.t. except for the constancy differences between *C. geyeri* and *C. rossii*, which are considered approximate ecological equivalents (see the POTR/SYOR/CAGE c.t. section). *Carex geyeri* is encountered most frequently in northern Utah, whereas the POTR-ABLA/CAGE type occurs most frequently in central and southern Utah.

The POTR-ABLA/CAGE c.t. is a seral stage within the *A. lasiocarpa* forest series (fig. 14), probably within the central and southern Utah *A. lasiocarpa/C. rossii* habitat type (Youngblood and Mauk 1985), judging from undergrowth similarities. The related habitat type for stands in northern Utah is uncertain.

Heavy grazing within the type leads to further simplification of what is basically rather species-poor undergrowth composition. Grazing tends to favor the dominance of such grazing-resistant species as *A. miser, F. vesca*, and *T. longipes*.

This is a good type for the production of trees and a poor type for the production of undergrowth. Tree growth was measured on 36 stands within the type. Basal area ranged from 93 to 320 ft^2/acre (21.3 to 73.4 m^2/ha) and averaged 199 ft^2/acre (45.6 m^2/ha). This was the highest average basal area for any of the community types we encountered. Conifers constituted 20 percent of the basal area. Aspen site index at 80 years ranged from 25 to 64 ft (7.6 to 19.5 m) and averaged a modest 48 ft (14.8 m). Aspen reproduction in these stands averaged a moderate 1,300 suckers/acre (3 300/ha), of which about a fourth were in the large 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer seedlings, 90 percent of which were *A. lasiocarpa*, averaged approximately 1,400 stems/acre (3 400/ha). About half of these were in the large size class.

Production of undergrowth on 31 stands averaged a low 271 lb/acre (304 kg/ha). Almost two-thirds of this

Figure 14.—*The Populus tremuloides-Abies lasiocarpa/Carex geyeri* c.t., common on the high plateaus of central and southern Utah, is a seral aspen type successional to *A. lasiocarpa* or *Picea engelmannii* forests, or both. Herbaceous undergrowth is usually sparse and consists of such species as *Carex rossii, Astragalus miser, Fragaria vesca*, and *Trifolium longipes*, as in this stand on the Aquarius Plateau, Dixie National Forest.

consisted of forbs and a third was graminoids. About half the undergrowth was considered to be in the desirable livestock forage category. The undergrowth provides poor livestock range primarily because of generally low productivity. Wildlife habitat values are usually low because the vegetation lacks diversity in both species composition and community structure.

This seral type has not been specifically identified as occurring outside of Utah. However, similar seral communities probably can be found at least in northwestern Colorado. Hoffman and Alexander (1980, 1983) identified an *A. lasiocarpa/C. geyeri* habitat type on the Routt and White River National Forests that has *P. tremuloides* as a major seral tree.

Populus tremuloides-Abies concolor/ Symphoricarpos oreophilus Community Type (POTR-ABCO/SYOR c.t.)

The POTR-ABCO/SYOR c.t., an intermediate elevation type, is widely scattered through central and southern Utah. It was most frequently encountered on the Wasatch Plateau and in the San Pitch Mountains. The 27 stands sampled in this type occurred at elevations ranging from 7,200 to 8,900 ft (2 190 to 2 710 m) and primarily on soils derived from sedimentary parent materials, usually sandstone.

This is one of two aspen-dominated types recognized as successional to an *Abies concolor* climax forest. Being the more moist of the two types, the undergrowth is characterized by an abundance of *Symphoricarpos oreophilus* in a distinct low shrub stratum and the conspicuous presence of members of the tall forb and tall grass groups in the herbaceous layer. The tree overstory contains substantial quantities of *A. concolor*, or occasionally *Picea pungens*. Frequently *Berberis repens* and *Rosa woodsii* are conspicuous shrub associates. No single species characterizes the herbaceous stratum. Instead, various combinations of *Aster engelmannii, Rudbeckia occidentalis, Agastache urticifolia, Mertensia arizonica, Senecio serra, Bromus carinatus, Elymus glaucus*, and *Agropyron trachycaulum* predominate. In addition, *Lathyrus* spp., *Osmorhiza chilensis*, and *Thalictrum fendleri* are frequent associates.

Given time and freedom from disturbance, stands within this community type will eventually succeed to *A. concolor* dominance. Undergrowth species' similarities suggest that the type most likely is a seral stage within *A. concolor/B. repens* or possibly *A. concolor/ O. chilensis* habitat types (Mauk and Henderson 1984; Youngblood and Mauk 1985). As *A. concolor* or *P. pungens* densities increase, and *Populus tremuloides* cover diminish, undergrowth production of tall herbs will give way to the more shade-tolerant *O. chilensis, T. fendleri*, and *B. repens*.

Under heavy cattle grazing, an increase in *R. occidentalis* and possibly *Lathyrus* spp. can be expected at the expense of the more palatable tall forbs and grasses. Heavy sheep use is likely to suppress *S. oreophilus* as well as the palatable tall forbs. Prolonged abusive grazing could lead to substantial increases in the abundance of the grazing-tolerant *Taraxacum officinale* and *Poa pratensis*.

The type apparently is able to support substantial tree basal area but at a rather low rate of growth. Stands sampled for productivity ranged in basal area from 106 to 215 ft^2/acre (24.2 to 49.3 m^2/ha) and averaged a high 177 ft^2/acre (40.7 m^2/ha). Conifers were 30 percent of this. Aspen site index at 80 years was generally low, ranging from 29 to 63 ft (8.8 to 19.2 m) and averaging only 42 ft (12.8 m). Aspen reproduction in these stands was also low. Less than 330 suckers/acre (800/ha) were produced on the average, of which about half were in the 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer reproduction averaged almost 650 stems/acre (1 600/ha), with 8 percent in the large size class. Over three-fourths of the conifer regeneration consisted of *A. concolor* seedlings.

Undergrowth production is generally low. Annual production ranged between 188 and 1,036 lb/acre (211 and 1 162 kg/ha), but averaged only 422 lb/acre (473 kg/ha). An average 39 percent of this was shrubs, 46 percent forbs, and 15 percent graminoids. What little vegetation was produced was generally considered good forage, with 51 percent in the desirable category. The type thus has relatively low value as livestock range because of sparse production. It appears to be of moderate value as wildlife habitat. Although undergrowth production is poor, considerable diversity exists in both overstory and undergrowth structure.

This seral aspen type has not been noted outside of Utah.

Populus tremuloides-Abies concolor/ Juniperus communis Community Type (POTR-ABCO/JUCO c.t.)

This is primarily a southern Utah seral community type that was encountered principally in the Tushar Mountains and high plateaus to the south. We also observed the type at several locations on the south slope of the Uinta Mountains in northern Utah. The 20 stands sampled occurred at elevations between 7,400 and 9,200 ft (2 260 and 2 800 m), usually on less than 25 percent slopes, and were not restricted by exposure. The type appears adapted to a wide variety of soil parent materials.

The POTR-ABCO/JUCO c.t. represents the drier segment of aspen stands that are successional to *Abies concolor* coniferous forests. The type is characterized by the conspicuous presence and potential dominance of *A. concolor* or *Picea pungens* in the tree overstory and a distinct low shrub layer dominated by *Juniperus communis*. Although *Symphoricarpos oreophilus* may be present in the shrub layer, it is usually of lesser abundance. The herbaceous undergrowth consists of a variable assortment of such graminoids as *Stipa occidentalis, Bromus anomalus, Carex rossii*, and *Sitanion hystrix*, and such forbs as *Astragalus miser, Achillea millefolium, Frageria vesca*, and *Thalictrum fendleri*.

The natural succession process leads to dominance by *A. concolor* or *P. pungens* or both in the tree layer and subsequent suppression of undergrowth production by

greater intensity of shading and competition. The type most likely represents a seral stage within either the *A. concolor/J. communis* or perhaps the *P. pungens/J. communis* habitat types that occur in central and southern Utah (Youngblood and Mauk 1985).

Heavy livestock use may lead to an increase in *J. communis* and *Berberis repens* in the shrub stratum, and an increase in *S. hystrix, A. miser, A. millefolium*, and *F. vesca* in the herbaceous layer. *Poa pratensis* and *Taraxacum officinale* are also likely to increase under abusive grazing.

Production was not sampled in this minor aspen type. Production of wood, however, is probably somewhat less than the 177 ft^2/acre (40.7 m^2/ha) basal area measured in the more moist POTR-ABCO/SYOR c.t. Undergrowth production is probably less than the low 422 lb/acre (473 kg/ha) measured for the POTR-ABCO/SYOR type. Composition of the undergrowth indicates moderately good forage suitability with 41 percent of the undergrowth cover in the desirable class. Lack of overall production makes this type rather poor livestock range. The type is of only moderate value as wildlife habitat.

This seral community type has not been noted outside of Utah.

Populus tremuloides-Pseudotsuga menziesii/Amelanchier alnifolia Community Type (POTR-PSME/AMAL c.t.)

This is a fairly local seral community type in the Bear River and Wasatch Ranges of northern Utah. One stand, however, was sampled in the LaSal Mountains of southeastern Utah. The type occurs at relatively low elevations. The northern Utah stands were at elevations between 6,000 and 7,850 ft (1 830 and 2 390 m). The stands occupied primarily steep, north-facing or east-facing slopes. They were on soils derived from sandstone, limestone, or quartzite parent materials.

The vegetation of this type consists of a complex, multilayered assemblage of species. The *Populus tremuloides*-dominated tree stratum includes *Pseudotsuga menziesii* as a prominent conifer constituent. A tall shrub element is generally dominated by *Amelanchier alnifolia, Prunus virginiana*, or *Acer grandidentatum*. A distinct low shrub layer also exists in which *Symphoricarpos oreophilus* is the usual dominant, but which also frequently contains *Pachistima myrsinites, Rosa woodsii*, and *Berberis repens*. The herbaceous stratum contains a wide and variable assortment of species. Potentially prominent grasses are *Bromus carinatus, Elymus glaucus*, and *Agropyron trachycaulum*. Occasionally the sedge *Carex geyeri* is abundant. The most constant and abundant forbs are *Osmorhiza chilensis, Thalictrum fendleri, Geranium viscosissimum, Lathyrus* spp., and *Smilacina racemosa*.

This type is a successional stage leading to a *P. menziesii* forest climax. Undergrowth species similarities suggest the type represents a seral stage within several different habitat types described by Mauk and Henderson (1984). These include the *P. menziesii/O. chilensis, P. menziesii/Acer glabrum*, and *P. menziesii/B. repens* habitat types.

Heavy livestock use is likely to cause a decrease in abundance of *S. oreophilus* and *A. alnifolia* and an increase in less palatable species such as *B. repens, Achillea millefolium*, and *G. viscosissimum*. In addition, heavy use by sheep will tend to suppress *O. chilensis, T. fendleri*, and *Lathyrus* spp. to the benefit of *B. carinatus, E. glaucus*, and *C. geyeri*. On the other hand, heavy cattle use will tend to suppress the graminoids and favor the forbs.

The type appears to be moderately productive for trees. Basal area averaged 160 ft^2/acre (36.7 m^2/ha) and ranged between 105 and 283 ft^2/acre (24.2 and 64.9 m^2/ha). An average 14 percent of this basal area consisted of conifers. Site index at 80 years for aspen ranged between 50 and 66 ft (15.2 and 20.1 m) and averaged a relatively high 60 ft (18.3 m). Aspen reproduction in these stands averaged a moderate 2,900 suckers/acre (7 200/ha), about half of which were in the 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer regeneration was not great. Only 338 stems/acre (836/ha) were recorded, and only 13 percent of these were in the large size class.

Undergrowth is not very productive in this type. It ranged between 561 and 994 lb/acre (630 and 1 115 kg/ha) and averaged a low to moderate 748 lb/acre (839 kg/ha). This production was well distributed among the various vegetation classes: 38 percent shrubs, 41 percent forbs, and 21 percent graminoids. Of the undergrowth, 45 percent was desirable forage and 47 percent of intermediate suitability. Thus, the type is rather mediocre range for livestock. However, it is considered good habitat for wildlife because of the great amount of vegetation diversity. The tree layer consists of both aspen and conifers, while the undergrowth is composed of tall shrubs, low shrubs, forbs, and graminoids.

Similar aspen communities seral to *P. menziesii*-dominated forests have been noted in Idaho and Wyoming. Mueggler and Campbell (1982) identified a similar *P. tremuloides-P. menziesii/P. virginiana* c.t. on the Caribou and Targhee National Forests. Youngblood and Mueggler (1981) observed a somewhat similar *P. tremuloides-P. menziesii/Spiraea betulifolia* type in eastern Wyoming; unlike the Utah type, however, theirs had an abundance of *Spiraea*. In addition, *P. tremuloides* was recognized by Steele and others (1983) as a major seral tree in both the *P. menziesii/O. chilensis* and *P. menziesii/B. repens* habitat types in eastern Idaho and western Wyoming.

Populus tremuloides-Pseudotsuga menziesii/Juniperus communis Community Type (POTR-PSME/JUCO c.t.)

The POTR-PSME/JUCO c.t. is a minor but widely distributed seral type. Five of the eight stands sampled were on the south slope of the Uinta Mountains in northern Utah. The remainder were on the Markagunt and Aquarius Plateaus in southern Utah. The type inhabits the upper elevation portion of the *Pseudotsuga menziesii* zone, with three-fourths of the stands at elevations exceeding 8,000 ft (2 440 m). The stands were primarily on relatively gentle slopes and on soils derived from either sedimentary or volcanic parent materials.

This community type is the drier of the two aspen types identified as successional to a climax *P. menziesii* forest. The vegetation is characterized by the conspicuous presence of *P. menziesii* in the tree layer, absence of a distinct tall shrub stratum, and the prominence of *Juniperus communis* in the low shrub layer. Occasionally *Pinus contorta* will also occur in some abundance in the tree layer. *Symphoricarpos oreophilus* and *Berberis repens* are frequent and often abundant members of the low shrub layer. The herbaceous stratum usually consists of a variable mixture of grasses and forbs. The most consistently occurring grasses are *Stipa occidentalis, Agropyron trachycaulum, Poa fendleriana,* and *Sitanion hystrix.* Frequently prominent forbs are *Astragalus miser, Fragaria vesca, Lupinus argenteus,* and *Taraxacum officinale.* Species diversity is ordinarily low.

The type is recognized as a seral stage within the *P. menziesii* climax forest series. It appears most closely related to the *P. menziesii/B. repens* and *P. menziesii/S. oreophilus* habitat types described by Mauk and Henderson (1984) for northern Utah and by Youngblood and Mauk (1985) for central and southern Utah.

Heavy livestock grazing tends to favor the production of *B. repens, A. miser, Fragaria vesca,* and *T. officinale* at the expense of *P. fendleriana, S. occidentalis, A. trachycaulum,* and *S. oreophilus.*

Production was not sampled in this infrequently encountered type. However, production of both trees and undergrowth will probably be somewhat less than in the more moist POTR-PSME/AMAL c.t., which averaged 160 ft^2/acre (36.7 m^2/ha) of tree basal area and 748 lb/acre (839 kg/ha) of undergrowth. Composition of the undergrowth indicates moderately good forage suitability for livestock, with 41 percent desirable and 48 percent intermediate. Value of the type as wildlife habitat is low to moderate, considerably less than in the POTR-PSME/AMAL c.t., because of the absence of a tall shrub layer.

This seral community type has not been reported to occur elsewhere.

Populus tremuloides-Pinus ponderosa/ Quercus gambelii Community Type (POTR-PIPO/QUGA c.t.)

This minor seral community type is in the LaSal and Abajo Mountains, the Aquarius Plateau, and as far north as the southern edge of the Uinta Mountains. The six sampled stands grew at elevations between 7,500 and 8,800 ft (2 290 and 2 680 m), primarily on gently sloping, southerly exposures. The majority of stands occurred on soils derived from sandstone parent material, but volcanic soils also support the type.

The vegetation of this community type is unique because of the presence of *Pinus ponderosa* as virtually the sole conifer associated with *Populus tremuloides* in the tree stratum and the presence of a tall shrub element in the undergrowth. *Quercus gambelii* is usually the primary tall shrub species, but *Prunus virginiana* or *Acer grandidentatum* may fill this role. Frequently *Symphoricarpos oreophilus* forms a distinct low shrub layer. The herbaceous undergrowth is usually rather sparse and consists of such species as *Achillea millefolium, Thermopsis montana, Thalictrum fendleri, Ligusticum porteri, Poa pratensis,* and *Taraxacum officinale.*

Normal succession in this type slowly leads to *P. tremuloides* replacement by *P. ponderosa.* In northern Utah the type is most likely a seral stage with the *P. ponderosa/Carex geyeri* habitat type (Mauk and Henderson 1984), whereas in central and southern Utah it probably is within either the *P. ponderosa/Q. gambelii* or *P. ponderosa/S. oreophilus* habitat types (Youngblood and Mauk 1985).

Only a single stand in this type was sampled for productivity. Tree basal area was a fairly high 170 ft^2/acre (39.1 m^2/ha), of which 26 percent was conifers. Aspen site index at 80 years was a low 40 ft (12.2 m). Only 567 suckers/acre (1 402/ha) were encountered in this stand; a third of these were in the 1- to 4.6-ft (0.3- to 1.4-m) size class. Only 13 conifer seedlings/acre (32/ha) were present, all of which were *P. ponderosa* in the large size class.

Production of undergrowth was a low 707 lb/acre (794 kg/ha). This was about equally divided between shrubs, forbs, and graminoids. A relatively high 50 percent of this was classified as desirable and 42 percent of intermediate forage suitability. The type is considered poor to fair range for livestock and at least moderate to good wildlife habitat.

This community type has not been identified outside of Utah.

Populus tremuloides-Pinus ponderosa/ Juniperus communis Community Type (POTR-PIPO/JUCO c.t.)

The POTR-PIPO/JUCO c.t. is a minor but widely dispersed type observed along the eastern portion of the Uinta Mountains in northern Utah and on the Markagunt and Aquarius Plateaus in southern Utah. The 14 stands sampled in this type occurred at elevations between 7,600 and 8,900 ft (2 320 and 2 710 m), on gentle slopes, and on soils derived from a wide variety of parent materials.

This is the most common of the two community types where *Pinus ponderosa* becomes prominently associated with aspen (fig. 15). The undergrowth in this type is characterized by the virtual absence of tall shrubs and the prominence of *Juniperus communis* in the low shrub layer. *Symphoricarpos oreophilus* and *Berberis repens* frequently accompany *J. communis* in the low shrub layer. The usually sparse herb stratum consists of a variable mixture of such relatively dry-site grasses as *Sitanion hystrix, Stipa comata,* and *Poa fendleriana,* and such forbs as *Astragalus miser, Antennaria microphylla, Fragaria vesca,* and *Taraxacum officinale.* None of these herbaceous species has high constancy.

This aspen-dominated type is considered a seral stage within the *P. ponderosa* forest series. It appears most closely associated with the *P. ponderosa/Festuca idahoensis* habitat type (Mauk and Henderson 1984) of northern Utah, and possibly the *P. ponderosa/*

Figure 15.—The minor though wide-ranging *Populus tremuloides-Pinus ponderosa/Juniperus communis* c.t. represents one of the driest aspen types successional to coniferous forests. This stand on the Markagunt Plateau, Dixie N.F., has typically sparce undergrowth in which *J. communis, Poa fendleriana, Sitanion hystrix, Antennaria rosea,* and *Achillea millefolium* are prominent species.

S. oreophilus habitat type (Youngblood and Mauk 1985) of central and southern Utah.

Production was sampled on only one stand in this type. Tree basal area was 193 ft^2/acre (44.3 m^2/ha) in this stand, which appears to be high for the *P. ponderosa* climax forest series. Conifers were 42 percent of the basal area. Aspen site index at 80 years was a fairly high 57 ft (17.4 m). Reproduction was low for both aspen and conifers. Only 450 aspen suckers/acre (1 114/ha) and 51 conifer seedlings/acre (127/ha) were counted.

Undergrowth production was a low 428 lb/acre (480 kg/ha). An unusually high 65 percent of this was graminoids, 15 percent forbs, and 20 percent shrubs. Though meager in amount, the undergrowth was highly rated as livestock forage, with 55 percent classed desirable and 43 percent as intermediate suitability. The high proportion of grasses makes this type better suited as cattle range than as sheep range. Wildlife habitat values appear low to moderate because of limited structural and species diversity of the vegetation.

This seral aspen type has not been reported to occur elsewhere.

Populus tremuloides-Pinus contorta/ Vaccinium scoparium Community Type (POTR-PICO/VASC c.t.)

This minor, local type occurred only on the north slope of the Uinta Mountains in northern Utah. The six sampled stands occupied only soils of quartzite origin. They grew at elevations between 7,700 and 9,100 ft (2 350 and 2 770 m).

The community type is characterized by the abundance of *Pinus contorta* associated with *Populus tremuloides* in the overstory and a low shrub complex dominated by *Vaccinium scoparium* or possibly *Vaccinium caespitosum*. Frequently *Abies lasiocarpa* may also be present in the tree layer but only in minor amounts. Shrubs likely to be encountered in the undergrowth associated with the *Vaccinium* spp. include *Berberis repens, Pachistima myrsinites,* and *Juniperus communis*. The only herbaceous species with high constancy and coverage is the sedge *Carex geyeri*. Other herbs often present in varying amounts include *Osmorhiza chilensis, Galium boreale, Elymus glaucus, Trisetum spicatum, Lathyrus* spp., *Arnica latifolia,* and *Antennaria microphylla*.

Mauk and Henderson (1984) recognized a *P. contorta/ V. scoparium* c.t. in the Uinta Mountains that resembles our POTR-PICO/VASC type. *P. contorta* is more shade tolerant than *P. tremuloides* and will eventually dominate these stands. *Abies lasiocarpa*, on the other hand, is more shade tolerant than *P. contorta* and where adapted will eventually replace *P. contorta*. Mauk and Henderson (1984) suggest that on some sites the *P. contorta/V. scoparium* c.t. reflects true climax vegetation and thus qualifies as a habitat type. On other sites this conifer type appears to be a successional stage within an *A. lasiocarpa/V. scoparium* habitat type. Thus, it appears that the POTR-PICO/VASC c.t. is a seral stage within both the *P. contorta/V. scoparium* and *A. lasiocarpa/V. scoparium* habitat types. In any event, the natural course of succession on these sites will lead to the demise of the aspen overstory and conifer dominance.

This minor type was not sampled for production. We assume, however, that tree growth may be approximately the same, if not slightly greater, than the 135 ft^2/acre (31.0 m^2/ha) basal area in POTR-PICO/JUCO type. Aspen site index in this latter type was a low 42 ft (12.9 m) at 80 years. Undergrowth production also may be similar to the low 603 lb/acre (677 kg/ha) found in the POTR-PICO/JUCO c.t. The POTR-PICO/VASC c.t. is relatively poor livestock range and of no more than moderate value as wildlife habitat.

Although this seral type has not been reported elsewhere, it probably can occur in Colorado. We believe that this type is probably seral to the *A. lasiocarpa/ V. scoparium* habitat type (Mauk and Henderson 1984) in Utah; *P. tremuloides* is also recognized as a seral tree in the same habitat type in northwestern Colorado (Hoffman and Alexander 1980, 1983).

Populus tremuloides-Pinus contorta/ Juniperus communis Community Type (POTR-PICO/JUCO c.t.)

The POTR-PICO/JUCO c.t. is a local seral type encountered only in the Uinta Mountains of northern Utah, where it is fairly common. It occurs on both the north and south flanks of this range at elevations usually above 8,000 ft (2 440 m). The 29 stands sampled in this type were not restricted by either slope or exposure but were confined primarily to soils derived from either sandstone or quartzite parent materials.

This is the more common of the two community types in which *Pinus contorta* is strongly associated with *Populus tremuloides* in the tree overstory. The undergrowth is composed of a low shrub layer dominated by *Juniperus communis* and an herb layer in which various graminoids are usually prominent. *Berberis repens* and *Rosa woodsii* are the shrubs most commonly associated with *J. communis*, but occasionally *Arctostaphylos uva-ursi* or *Symphoricarpos oreophilus* may occur in some abundance. *Carex geyeri, Stipa occidentalis, Agropyron trachycaulum*, and *Bromus ciliatus* are usually the most prominent graminoids. The forb component consists of a mixture of species. The most common are *Achillea millefolium, Astragalus miser, Lupinus argenteus, Geranium viscosissimum, Thalictrum fendleri, Antennaria microphylla, Fragaria vesca*, and *Potentilla gracilis*.

The seral status of the POTR-PICO/JUCO c.t. is apparent from the abundance of *P. contorta* in the tree overstory. Succession is obviously away from dominance by *P. tremuloides* and toward dominance by the more shade-tolerant conifer. Undergrowth similarities suggest that succession may be toward the *P. contorta/B. repens* or possibly the *P. contorta/J. communis* community types. Mauk and Henderson (1984) indicate that the *P. contorta/B. repens* type is climax in some situations. In others, particularly where *C. geyeri* is abundant and *Abies lasiocarpa* is present, it is a seral type within the *A. lasiocarpa/B. repens* habitat type. Mauk and Henderson consider the *P. contorta/J. communis* community type to be primarily a seral stage within the *A. lasiocarpa/J. communis* habitat type. Thus, the POTR-PICO/JUCO type may represent a seral stage within at least three habitat types: *P. contorta/B. repens, A. lasiocarpa/B. repens*, and *A. lasiocarpa/J. communis*.

Tree production within this type is low to moderate. Basal area ranged from 104 to 178 ft^2/acre (23.8 to 40.8 m^2/ha) and averaged 135 ft^2/acre (31.0 m^2/ha). Of this basal area, 16 percent was conifers, primarily *P. contorta*. Aspen site index at 80 years ranged from 37 to 51 ft (11.3 to 15.5 m) and averaged a low 42 ft (12.9 m). Aspen reproduction averaged a low 676 suckers/acre (1 670/ha), but 70 percent of these were in the 1- to 4.6-ft (0.3- to 1.4-m) size class. Conifer regeneration averaged 236 seedlings/acre (584/ha), of which 30 percent were in the larger size class. Approximately half of these seedlings were *P. contorta*, the other half *Abies lasiocarpa*.

Undergrowth production is low, ranging from 290 to 824 lb/acre (326 to 925 kg/ha) and averaging only 603 lb/acre (677 kg/ha). Of this, 8 percent was shrubs, primarily *J. communis*, 71 percent forbs, and 21 percent graminoids. The undergrowth is moderately desirable as forage with 44 percent in the desirable class and 51 percent in the intermediate class. But this type is rather poor range for livestock because of low forage production. It has only moderate value as wildlife habitat.

This seral type is not known to occur outside of the Uinta Mountains in northeastern Utah.

REFERENCES

Arnow, L.; Wyckoff, A.; Albee, B. Flora of the central Wasatch Front. Salt Lake City, UT: University of Utah Printing Service; 1977. 459 p.

Bunin, J. E. The vegetation of the west slope of the Park Range, Colorado. Boulder, CO: University of Colorado; 1975. 270 p. Ph.D. dissertation.

Daubenmire, R.; Daubenmire, J. B. Forest vegetation of eastern Washington and northern Idaho. Technical Bulletin 60. Pullman, WA: Washington Agricultural Experiment Station; 1968. 104 p.

Dorn, R. D. Manual of the vascular plants of Wyoming. New York: Garland Publishing; 1977. 1498 p.

Green, A. W.; Van Hooser, D. D. Forest resources of the Rocky Mountain States. Resource Bulletin INT-33. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 127 p.

Harper, K. T. The influence of tree overstory on understory production and composition in aspen forests of central Utah. Society of Range Management. Abstracts. 1973: 22.

Harrington, H. D. Manual of plants of Colorado. Denver, CO: Sage Books; 1954. 665 p.

Hitchcock, C. L.; Cronquist, A. Flora of the Pacific Northwest. Seattle, WA: University of Washington Press; 1973. 730 p.

Hoffman, G. R.; Alexander, R. R. Forest vegetation of the Routt National Forest in northwestern Colorado: a habitat type classification. Research Paper RM-221. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1980. 41 p.

Hoffman, G. R.; Alexander, R. R. Forest vegetation of the White River National Forest in western Colorado: a habitat type classification. Research Paper RM-249. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1983. 36 p.

Jones, J. R. Aspen site index in the Rocky Mountains. Journal of Forestry. 65(11): 820-821; 1967.

Langenheim, J. H. Vegetation and environmental patterns in the Crested Butte area, Gunnison County, Colorado. Ecological Monographs. 32(3): 249-285; 1962.

Lewis, M. E. Plant communities of the Jarbridge Mountain complex. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region; 1975. 22 p.

Martin, W. C.; Hutchins, C. R. A flora of New Mexico. Hirschberg, Germany: Strauss and Cramer; 1980. 2591 p.

Mauk, R. L.; Henderson, J. A. Coniferous forest habitat types of northern Utah. General Technical Report INT-170. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 89 p.

Mueggler, W. F.; Campbell, R. B. Aspen community types on the Caribou and Targhee National Forests in southeastern Idaho. Research Paper INT-294. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 32 p.

Mueller-Dombois, D.; Ellenberg, H. Aims and methods of vegetation ecology. New York: John Wiley and Sons; 1974. 547 p.

Schlatterer, E. F. A preliminary description of plant communities found on the Sawtooth, White Cloud, Boulder, and Pioneer Mountains. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region; 1972. 111 p.

Steele, R.; Cooper, S. V.; Ondov, D. M.; Roberts, D. W.; Pfister, R. D. Forest habitat types of eastern Idaho-western Wyoming. General Technical Report INT-144. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 122 p.

U.S. Department of Agriculture, Forest Service. Range environmental analysis handbook: Intermountain Region. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region; 1981. 240 p. [Multilithed.]

Welsh, S. L.; Moore, G. Utah plants: Tracheophyta. Provo, UT: Brigham Young University Press; 1973. 474 p.

Wirsing, J. M.; Alexander, R. R. Forest habitat types on the Medicine Bow National Forest, southeastern Wyoming: preliminary report. General Technical Report RM-12. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1975. 11 p.

Youngblood, A. P.; Mauk, R. L. Coniferous forest habitat types of central and southern Utah. General Technical Report INT-187. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1985. 89 p.

Youngblood, A. P.; Mueggler, W. F. Aspen community types on the Bridger-Teton National Forest in western Wyoming. Research Paper INT-272. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 32 p.

APPENDIX A: CONSTANCY AND AVERAGE CANOPY COVER (LATTER IN PARENTHESES) OF IMPORTANT PLANT SPECIES IN ASPEN COMMUNITY TYPES IN UTAH

	ALL STANDS CLAS-SIFIED	POTR/ ACGR/ PTAQ C.T.	POTR/ PRVI/ SESE C.T.	POTR/ PRVI/ CAGE C.T.	POTR/ SARA C.T.	POTR/ SYOR/ SESE C.T.	POTR/ SYOR/ CAGE C.T.	POTR/ SYOR/ FETH C.T.	POTR/ SYOR/ BRCA C.T.	POTR/ SYOR/ POPR C.T.	POTR/ JUCO/ CAGE C.T.
Number of Stands:	1179	11	114	12	16	151	61	7	12	30	70
TREES											
ABIES CONCOLOR	10(8)	27(3)	14(1)	17(T)	-(-)	17(1)	5(7)	14(T)	8(T)	-(-)	4(4)
ABIES LASIOCARPA	38(12)	9(1)	6(1)	8(3)	31(2)	23(T)	23(1)	-(-)	50(1)	3(T)	17(1)
PICEA ENGELMANNII	13(7)	-(-)	1(T)	-(-)	6(T)	1(2)	10(1)	29(T)	-(-)	3(1)	16(T)
PICEA PUNGENS	5(7)	-(-)	-(-)	(-)	-(-)	1(T)	3(1)	-(-)	-(-)	7(T)	9(1)
PINUS CONTORTA	10(11)	-(-)	1(4)	8(4)	-(-)	1(1)	-(-)	-(-)	17(6)	7(2)	33(2)
PINUS FLEXILIS	5(2)	-(-)	-( )	-(-)	-(-)	-(-)	8(T)	-(-)	-(-)	3(T)	7(T)
PINUS PONDEROSA	5(10)	-(-)	-(-)	8(T)	-(-)	-(-)	5(T)	14(T)	-(-)	13(1)	6(1)
POPULUS TREMULOIDES	100(72)	100(71)	100(76)	100(78)	100(71)	100(71)	100(78)	100(83)	100(65)	100(73)	100(76)
PSEUDOTSUGA MENZIESII	17(4)	-(-)	12(2)	17(T)	-(-)	8(1)	39(2)	43(3)	25(2)	7(1)	23(1)
SHRUBS											
ACER GLABRUM	1(2)	9(T)	4(4)	-(-)	-(-)	1(1)	2(T)	-(-)	-(-)	-(-)	1(2)
ACER GRANDIDENTATUM	10(13)	91(16)	46(19)	33(41)	-(-)	8(T)	5(T)	-(-)	17(3)	13(1)	1(T)
AMELANCHIER ALNIFOLIA	26(5)	55(6)	72(9)	92(10)	6(2)	27(2)	28(1)	14(T)	50(2)	30(2)	19(1)
ARCTOSTAPHYLOS UVA-URSI	3(6)	-(-)	-(-)	17(2)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	16(8)
ARTEMISIA TRIDENTATA	9(4)	-(-)	3(4)	-(-)	-(-)	10(3)	13(T)	-(-)	17(1)	20(2)	31(8)
BERBERIS REPENS	36(5)	36(22)	49(5)	75(16)	-(-)	21(3)	43(8)	71(17)	67(1)	43(6)	51(7)
CEANOTHUS VELUTINUS	1(7)	-(-)	4(7)	17(19)	-(-)	1(T)	-(-)	-(-)	17(10)	-(-)	-(-)
CHRYSOTHAMNUS VISCIDIFLORUS	2(4)	-(-)	1(T)	8(T)	-(-)	1(T)	5(7)	-(-)	8(1)	7(T)	3(33)
JUNIPERUS COMMUNIS	25(9)	-(-)	2(1)	25(4)	-(-)	1(T)	16(1)	29(12)	8(T)	23(7)	96(15)
PACHISTIMA MYRSINITES	12(4)	9(1)	24(11)	50(5)	-(-)	6(1)	11(1)	-(-)	25(1)	7(T)	3(T)
PHYSOCARPUS MALVACEUS	3(13)	18(11)	11(14)	25(19)	6(5)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
PRUNUS VIRGINIANA	19(12)	82(10)	86(23)	83(13)	6(5)	29(2)	11(6)	-(-)	17(T)	23(2)	-(-)
QUERCUS GAMBELII	4(7)	9(10)	11(2)	33(22)	-(-)	2(T)	5(3)	-(-)	8(5)	10(3)	-(-)
RIBES LACUSTRE	2(5)	-(-)	2(38)	-(-)	6(5)	3(1)	-(-)	-(-)	-(-)	7(3)	1(3)
RIBES MONTIGENUM	3(2)	-(-)	-(-)	-(-)	25(6)	1(10)	-(-)	-(-)	-(-)	-(-)	-(-)
RIBES SP.	7(1)	-(-)	10(1)	8(T)	19(3)	7(T)	11(1)	-(-)	-(-)	-(-)	3(1)
ROSA WOODSII	36(2)	55(2)	56(3)	83(2)	6(T)	34(1)	56(2)	86(5)	42(1)	33(6)	39(1)
RUBUS PARVIFLORUS	3(4)	9(T)	5(2)	-(-)	6(T)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
SALIX SCOULERIANA	3(3)	-(-)	5(4)	8(8)	6(10)	1(3)	-(-)	-(-)	-(-)	-(-)	-(-)
SAMBUCUS RACEMOSA	14(3)	27(2)	17(2)	-(-)	88(20)	15(2)	3(T)	-(-)	-(-)	3(T)	1(T)
SHEPHERDIA CANADENSIS	3(1)	-(-)	3(T)	-(-)	-(-)	1(T)	2(T)	-(-)	-(-)	-(-)	1(T)
SORBUS SCOPULINA	2(4)	-(-)	4(17)	-(-)	13(5)	1(2)	-(-)	-(-)	-(-)	-(-)	-(-)
SYMPHORICARPOS OREOPHILUS	74(18)	55(7)	93(25)	83(20)	44(3)	100(32)	100(33)	100(26)	100(27)	100(29)	79(8)
VACCINIUM CAESPITOSUM	1(7)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
VACCINIUM SCOPARIUM	1(8)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
GRAMINOIDS											
AGROPYRON TRACHYAULUM	56(4)	45(T)	46(3)	67(4)	69(2)	68(4)	61(6)	43(1)	83(7)	67(3)	70(3)
ARRHENATHERUM ELATIUS	1(11)	9(T)	1(T)	-(-)	-(-)	1(22)	-(-)	-(-)	8(T)	3(45)	-(-)
BROMUS ANOMALUS	9(7)	-(-)	2(20)	-(-)	-(-)	-(-)	18(5)	57(8)	-(-)	-(-)	11(22)
BROMUS CARINATUS	48(10)	64(7)	59(5)	33(1)	81(19)	79(9)	15(5)	-(-)	100(24)	30(1)	20(5)
BROMUS CILIATUS	12(3)	-(-)	4(5)	33(4)	-(-)	1(T)	13(3)	29(3)	8(T)	7(5)	26(2)
CALAMAGROSTIS RUBESCENS	1(27)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
CAREX GEYERI	20(16)	-(-)	14(2)	75(25)	6(2)	7(6)	41(25)	-(-)	8(T)	-(-)	61(21)
CAREX HOODII	15(3)	-(-)	20(1)	8(3)	25(2)	24(2)	8(4)	-(-)	33(3)	7(T)	7(1)
CAREX OBTUSATA	1(11)	-(-)	-(-)	-(-)	-(-)	-(-)	3(20)	-(-)	-(-)	-(-)	1(4)
CAREX ROSSII	15(4)	-(-)	3(1)	-(-)	-(-)	1(T)	11(6)	-(-)	8(1)	10(1)	17(3)
DACTYLIS GLOMERATA	6(5)	9(T)	6(6)	-(-)	-(-)	13(3)	-(-)	-(-)	17(15)	10(2)	-(-)
ELYMUS CINEREUS	1(8)	-(-)	4(2)	-(-)	-(-)	3(23)	-(-)	-(-)	8(T)	10(1)	-(-)
ELYMUS GLAUCUS	33(12)	82(16)	74(15)	42(5)	44(9)	48(10)	16(5)	-(-)	67(13)	10(4)	4(5)
FESTUCA IDAHOENSIS	3(4)	-(-)	-(-)	-(-)	-(-)	1(3)	7(5)	-(-)	-(-)	7(4)	10(6)
FESTUCA THURBERI	4(9)	-(-)	-(-)	8(3)	-(-)	-(-)	7(2)	100(15)	-(-)	3(T)	1(5)
KOELERIA CRISTATA	2(2)	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	4(1)
LEUCOPOA KINGII	1(4)	-(-)	2(2)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	3(1)	-(-)
MELICA SPECTABILIS	9(1)	-(-)	4(1)	17(T)	31(1)	8(T)	5(1)	-(-)	17(3)	3(T)	6(T)
PHLEUM ALPINUM	2(1)	-(-)	-(-)	-(-)	-(-)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
POA FENDLERIANA	7(3)	-(-)	-(-)	8(T)	-(-)	-(-)	15(3)	14(3)	8(T)	7(2)	11(6)
POA NERVOSA	16(2)	9(T)	15(2)	-(-)	31(2)	21(1)	5(9)	-(-)	8(T)	3(2)	6(1)
POA PRATENSIS	33(16)	27(1)	35(21)	33(21)	13(T)	37(19)	48(8)	14(10)	50(28)	97(31)	33(8)
SITANION HYSTRIX	9(3)	-(-)	-(-)	-(-)	-(-)	-(-)	18(1)	29(T)	-(-)	7(T)	10(1)
STIPA COMATA	4(8)	-(-)	-(-)	-(-)	-(-)	-(-)	5(4)	-(-)	-(-)	3(T)	10(4)
STIPA LETTERMANII	7(3)	-(-)	1(T)	-(-)	6(T)	1(T)	18(6)	14(2)	-(-)	10(T)	9(3)
STIPA OCCIDENTALIS	33(6)	9(T)	12(1)	58(18)	13(2)	17(2)	67(9)	43(3)	33(8)	17(2)	86(8)
TRISETUM SPICATUM	8(1)	-(-)	-(-)	-(-)	13(T)	-(-)	2(T)	-(-)	-(-)	-(-)	14(1)

APPENDIX A. (Con.)

	ALL STANDS CLAS-SIFIED	POTR/ ACGR/ PTAQ C.T.	POTR/ PRVI/ SESE C.T.	POTR/ PRVI/ CAGE C.T.	POTR/ SARA C.T.	POTR/ SYOR/ SESE C.T.	POTR/ SYOR/ CAGE C.T.	POTR/ SYOR/ FETH C.T.	POTR/ SYOR/ BRCA C.T.	POTR/ SYOR/ POPR C.T.	POTR/ JUCO/ CAGE C.T.
Number of Stands:	1179	11	114	12	16	151	61	7	12	30	70
FORBS											
ACHILLEA MILLEFOLIUM	58(2)	9(T)	55(1)	42(1)	50(T)	52(1)	62(1)	86(T)	75(1)	63(1)	67(2)
ACTAEA RUBRA	4(4)	9(1)	5(3)	-(-)	19(1)	4(2)	-(-)	-(-)	-(-)	-(-)	-(-)
AGASTACHE URTICIFOLIA	29(5)	36(6)	68(6)	8(T)	31(6)	68(5)	3(T)	-(-)	8(T)	13(T)	-(-)
AGOSERIS GLAUCA	6(T)	-(-)	3(T)	-(-)	13(T)	3(T)	3(T)	-(-)	8(T)	-(-)	17(T)
ALLIUM BREVISTYLUM	3(1)	-(-)	5(T)	-(-)	-(-)	9(T)	-(-)	-(-)	-(-)	7(T)	3(T)
ALLIUM CERNUUM	2(T)	-(-)	-(-)	8(T)	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	10(T)
ANTENNARIA MICROPHYLLA	11(2)	-(-)	-(-)	8(T)	-(-)	1(T)	15(1)	-(-)	-(-)	20(T)	41(3)
ANTENNARIA PARVIFOLIA	1(1)	-(-)	-(-)	-(-)	-(-)	-(-)	3(T)	-(-)	-(-)	-(-)	4(T)
APOCYNUM ANDROSAEMIFOLIUM	2(1)	9(T)	7(2)	17(1)	-(-)	-(-)	-(-)	-(-)	17(T)	-(-)	1(T)
AQUILEGIA COERULEA	16(1)	18(T)	8(1)	-(-)	38(1)	22(1)	16(T)	29(T)	-(-)	10(T)	13(1)
ARENARIA CONGESTA	2(1)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	14(1)
ARNICA CORDIFOLIA	5(2)	-(-)	4(5)	17(1)	-(-)	2(1)	2(T)	-(-)	-(-)	3(T)	3(T)
ARNICA LATIFOLIA	3(9)	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	3(8)
ARTEMISIA LUDOVICIANA	2(3)	-(-)	1(T)	-(-)	25(3)	2(14)	-(-)	14(T)	8(T)	3(T)	-(-)
ASTER CHILENSIS	4(1)	-(-)	8(T)	17(T)	-(-)	3(2)	8(2)	-(-)	17(T)	7(8)	3(T)
ASTER ENGELMANNII	23(3)	64(3)	56(4)	-(-)	38(1)	31(4)	3(2)	-(-)	8(T)	-(-)	-(-)
ASTER FOLIACEUS	2(3)	-(-)	2(2)	-(-)	-(-)	5(2)	-(-)	-(-)	-(-)	3(5)	-(-)
ASTER OCCIDENTALIS	1(12)	-(-)	1(3)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	6(18)
ASTRAGALUS MISER	15(10)	-(-)	2(T)	8(15)	-(-)	-(-)	23(11)	-(-)	8(T)	3(2)	51(13)
CAMPANULA ROTUNDIFOLIA	2(T)	-(-)	-(-)	8(T)	-(-)	-(-)	2(T)	-(-)	-(-)	7(T)	17(T)
CASTILLEJA MINIATA	12(1)	-(-)	10(T)	8(T)	6(2)	9(1)	11(T)	57(T)	-(-)	7(T)	23(T)
CHENOPODIUM FREMONTII	7(1)	-(-)	10(T)	-(-)	25(T)	7(1)	5(T)	14(T)	-(-)	-(-)	3(T)
CHLOROCRAMBE HASTATA	2(2)	-(-)	5(T)	-(-)	-(-)	3(3)	-(-)	-(-)	-(-)	-(-)	-(-)
CIRCAEA ALPINA	1(11)	27(8)	4(16)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
CIRSIUM ARVENSE	4(1)	-(-)	1(T)	-(-)	-(-)	3(T)	8(2)	-(-)	-(-)	-(-)	9(T)
CIRSIUM VULGARE	1(1)	-(-)	-(-)	8(T)	-(-)	2(1)	3(3)	-(-)	-(-)	-(-)	1(T)
CLEMATIS COLUMBIANA	2(1)	36(1)	2(T)	-(-)	6(T)	-(-)	-(-)	-(-)	-(-)	3(T)	-(-)
COLLINSIA PARVIFLORA	7(4)	-(-)	4(1)	-(-)	-(-)	6(3)	-(-)	-(-)	8(2)	-(-)	4(4)
COLLOMIA LINEARIS	12(3)	-(-)	9(1)	8(T)	31(2)	23(2)	2(T)	-(-)	8(2)	-(-)	-(-)
CORALLORHIZA MACULATA	4(T)	9(T)	3(T)	8(T)	-(-)	3(T)	2(T)	14(T)	8(T)	3(T)	3(T)
DELPHINIUM NUTTALLIANUM	7(T)	-(-)	2(T)	8(T)	-(-)	4(T)	13(T)	-(-)	-(-)	20(T)	7(T)
DELPHINIUM OCCIDENTALE	13(4)	27(2)	11(6)	-(-)	50(4)	22(5)	2(T)	14(T)	8(T)	-(-)	3(1)
DESCURAINIA CALIFORNICA	2(2)	-(-)	-(-)	-(-)	19(3)	3(1)	-(-)	-(-)	-(-)	-(-)	-(-)
DESCURAINIA RICHARDSONII	27(1)	36(1)	34(1)	8(T)	69(1)	41(1)	28(T)	43(T)	17(T)	10(T)	3(T)
EPILOBIUM ANGUSTIFOLIUM	5(T)	9(T)	9(1)	25(T)	-(-)	-(-)	3(T)	-(-)	8(T)	-(-)	6(T)
ERIGERON FLAGELLARIS	2(T)	-(-)	1(T)	-(-)	-(-)	1(T)	5(1)	-(-)	-(-)	3(T)	-(-)
ERIGERON PEREGRINUS	3(3)	-(-)	1(1)	8(5)	-(-)	1(1)	-(-)	-(-)	-(-)	-(-)	9(3)
ERIGERON SPECIOSUS	15(1)	-(-)	17(2)	8(T)	6(5)	25(2)	13(1)	-(-)	17(3)	7(3)	16(T)
ERIGERON URSINUS	1(1)	-(-)	-(-)	-(-)	-(-)	-(-)	3(T)	-(-)	-(-)	7(T)	3(T)
ERYTHRONIUM GRANDIFLORUM	2(2)	-(-)	1(3)	8(T)	13(5)	3(T)	-(-)	-(-)	-(-)	-(-)	-(-)
FRAGARIA VESCA	21(2)	-(-)	16(1)	25(T)	6(T)	14(3)	13(1)	14(T)	17(T)	3(T)	24(1)
FRASERA SPECIOSA	13(1)	-(-)	10(1)	25(1)	-(-)	11(1)	31(2)	14(T)	8(T)	7(T)	17(2)
GALIUM APARINE	1(4)	9(7)	5(1)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	1(1)
GALIUM BIFOLIUM	13(4)	18(2)	14(4)	-(-)	38(12)	24(2)	3(5)	-(-)	-(-)	-(-)	3(3)
GALIUM BOREALE	16(1)	45(2)	23(1)	33(T)	-(-)	9(1)	20(1)	-(-)	25(T)	13(1)	27(1)
GERANIUM RICHARDSONII	7(5)	-(-)	-(-)	8(T)	6(T)	7(5)	5(3)	-(-)	-(-)	3(2)	4(2)
GERANIUM VISCOSISSIMUM	31(3)	9(T)	39(3)	42(T)	13(T)	37(2)	33(2)	-(-)	67(5)	27(3)	59(6)
HABENARIA UNALASCENSIS	3(T)	-(-)	9(T)	8(T)	-(-)	-(-)	-(-)	-(-)	17(T)	-(-)	4(T)
HACKELIA FLORIBUNDA	25(3)	-(-)	37(2)	17(T)	31(2)	48(4)	7(2)	-(-)	33(4)	20(3)	7(T)
HAPLOPAPPUS PARRYI	2(2)	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	4(1)
HELENIUM HOOPESII	6(2)	-(-)	2(T)	-(-)	13(T)	1(3)	8(2)	29(T)	-(-)	20(1)	-(-)
HELIANTHELLA UNIFLORA	2(4)	-(-)	3(T)	-(-)	-(-)	2(2)	2(2)	-(-)	-(-)	3(T)	-(-)
HERACLEUM LANATUM	6(8)	27(6)	11(7)	-(-)	-(-)	10(3)	-(-)	-(-)	-(-)	-(-)	-(-)
HIERACIUM ALBIFLORUM	2(T)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	17(T)	-(-)	3(T)
HYDROPHYLLUM CAPITATUM	8(T)	9(T)	9(T)	8(T)	19(T)	13(T)	-(-)	-(-)	-(-)	-(-)	-(-)
HYDROPHYLLUM FENDLERI	1(18)	-(-)	3(38)	-(-)	6(20)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
IRIS MISSOURIENSIS	1(4)	-(-)	1(4)	-(-)	-(-)	-(-)	8(T)	-(-)	-(-)	10(T)	-(-)
LATHYRUS ARIZONICUS	1(31)	-(-)	-(-)	-(-)	-(-)	-(-)	5(24)	14(38)	-(-)	-(-)	-(-)
LATHYRUS LANSZWERTII	28(16)	18(5)	39(10)	17(7)	38(17)	42(17)	13(23)	43(18)	33(10)	13(9)	6(24)
LATHYRUS LEUCANTHUS	15(19)	9(13)	21(15)	17(17)	13(29)	13(13)	30(30)	29(18)	25(3)	17(12)	3(28)
LATHYRUS PAUCIFLORUS	6(3)	27(3)	14(7)	-(-)	19(1)	10(2)	-(-)	-(-)	8(T)	-(-)	-(-)
LIGUSTICUM FILICINUM	3(3)	-(-)	-(-)	-(-)	25(4)	3(1)	2(T)	-(-)	-(-)	-(-)	1(T)
LIGUSTICUM PORTERI	11(3)	-(-)	3(10)	8(2)	19(T)	3(2)	38(3)	29(4)	-(-)	3(2)	10(3)
LUPINUS ARGENTEUS	23(7)	9(T)	17(4)	25(11)	-(-)	11(8)	43(5)	29(T)	17(10)	50(3)	56(9)
LUPINUS CAUDATUS	2(3)	-(-)	3(1)	-(-)	-(-)	3(2)	-(-)	-(-)	25(1)	7(1)	-(-)

APPENDIX A. (Con.)

	ALL STANDS CLAS-SIFIED	POTR/ ACGR/ PTAQ C.T.	POTR/ PRVI/ SESE C.T.	POTR/ PRVI/ CAGE C.T.	POTR/ SARA C.T.	POTR/ SYOR/ SESE C.T.	POTR/ SYOR/ CAGE C.T.	POTR/ SYOR/ FETH C.T.	POTR/ SYOR/ BRCA C.T.	POTR/ SYOR/ POPR C.T.	POTR/ JUCO/ CAGE C.T.
Number of Stands:	1179	11	114	12	16	151	61	7	12	30	70
FORBS (CONT'D)											
MERTENSIA ARIZONICA	20(8)	9(5)	25(4)	8(T)	50(14)	37(8)	3(T)	14(T)	-(-)	3(T)	-(-)
MERTENSIA CILIATA	1(10)	-(-)	2(3)	-(-)	6(10)	( )	-(-)	-(-)	-(-)	-(-)	-(-)
MERTENSIA FRANCISCANA	2(7)	-(-)	1(T)	-(-)	6(3)	-(-)	7(5)	-(-)	-(-)	3(T)	-(-)
MERTENSIA LONGIFLORA	1(9)	-(-)	3(T)	-(-)	-(-)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
NEMOPHILA BREVIFLORA	15(14)	45(12)	19(6)	-(-)	25(11)	28(11)	-( )	-(-)	8(T)	3(10)	-(-)
OSMORHIZA CHILENSIS	37(3)	64(5)	50(4)	25(6)	50(2)	40(3)	23(2)	-(-)	33(T)	23(4)	21(2)
OSMORHIZA OCCIDENTALIS	15(3)	9(5)	20(3)	-(-)	69(7)	24(3)	5(T)	-(-)	8(T)	-(-)	-(-)
PEDICULARIS RACEMOSA	1(6)	-(-)	(-)	-(-)	(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
PENSTEMON PROCERUS	1(3)	-(-)	-(-)	-(-)	-(-)	-(-)	3(2)	-(-)	-(-)	-(-)	1(1)
PENSTEMON RYDBERGII	2(1)	-(-)	-(-)	-(-)	6(T)	5(1)	3(1)	-(-)	-(-)	-(-)	3(T)
PHACELIA HETEROPHYLLA	12(1)	18(T)	28(T)	(-)	13(T)	24(1)	5(T)	14(T)	8(T)	17(1)	-(-)
POLEMONIUM FOLIOSISSIMUM	16(2)	27(T)	21(1)	-(-)	69(2)	30(2)	3(T)	-(-)	-( )	-(-)	1(T)
POLYGONUM DOUGLASII	17(3)	18(3)	25(1)	8(T)	44(2)	26(4)	7(5)	-(-)	8(2)	-(-)	10(T)
POTENTILLA DIVERSIFOLIA	2(1)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	7(T)	4(T)
POTENTILLA GLANDULOSA	8(1)	-(-)	6(T)	8(T)	13(T)	9(1)	10(1)	-(-)	42(T)	10(T)	1(T)
POTENTILLA GRACILIS	12(1)	-(-)	1(T)	8(T)	-( )	6(T)	11(1)	43(T)	17(1)	3(T)	51(1)
PTERIDIUM AQUILINUM	2(46)	100(44)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
RANUNCULUS INAMOENUS	4(T)	-(-)	3(T)	-(-)	19(T)	1(T)	5(T)	-(-)	-(-)	-(-)	1(T)
RUDBECKIA OCCIDENTALIS	33(9)	36(6)	38(4)	8(2)	38(14)	67(10)	7(T)	-(-)	8(T)	7(2)	-(-)
SCROPHULARIA LANCEOLATA	9(1)	36(T)	18(T)	-(-)	13(3)	15(1)	-(-)	-(-)	-(-)	-(-)	-(-)
SENECIO CYMBALARIOIDES	10(1)	-(-)	21(1)	8(T)	(-)	15(1)	3(1)	-(-)	25(T)	3(T)	3(3)
SENECIO INTEGERRIMUS	2(1)	-(-)	1(2)	-(-)	-(-)	1(T)	2(T)	-(-)	-(-)	7(T)	4(1)
SENECIO SERRA	24(4)	27(9)	45(4)	-(-)	31(4)	54(5)	-(-)	-(-)	8(T)	-(-)	1(2)
SENECIO VULGARIS	3(1)	-(-)	-(-)	-(-)	-(-)	1(T)	2(5)	14(T)	-(-)	10(T)	-(-)
SIDALCEA OREGANA	2(1)	-(-)	3(T)	-(-)	-(-)	6(T)	-(-)	-(-)	17(T)	-(-)	1(T)
SILENE MENZIESII	7(1)	18(T)	12(1)	25(1)	-( )	3(1)	2(1)	-( )	-(-)	3(T)	1(T)
SMILACINA RACEMOSA	4(1)	27(T)	9(1)	17(T)	-(-)	3(T)	2(T)	-(-)	-(-)	3(T)	-(-)
SMILACINA STELLATA	17(3)	45(17)	28(4)	58(12)	25(T)	15(1)	23(2)	43(1)	-(-)	7(T)	13(1)
STELLARIA JAMESIANA	36(2)	27(1)	41(3)	8(2)	56(9)	46(2)	21(1)	14(T)	8(T)	20(T)	29(2)
TARAXACUM OFFICINALE	46(3)	27(T)	31(T)	33(T)	25(T)	28(1)	59(3)	72(7)	33(2)	70(4)	70(7)
THALICTRUM FENDLERI	49(7)	45(2)	68(12)	42(5)	75(13)	52(8)	41(9)	43(3)	33(1)	37(3)	44(6)
THERMOPSIS MONTANA	3(5)	9(T)	1(7)	8(7)	-(-)	-(-)	3(2)	-(-)	-(-)	10(5)	4(6)
TRAGOPOGON DUBIUS	4(T)	-(-)	7(T)	-(-)	-(-)	5(T)	2(T)	-( )	17(T)	10(1)	-(-)
TRIFOLIUM LONGIPES	6(8)	9(T)	-(-)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	3(2)	13(7)
URTICA DIOICA	2(1)	18(5)	2(3)	-(-)	13(T)	2(T)	-(-)	-(-)	-(-)	-(-)	-(-)
VALERIANA OCCIDENTALIS	24(5)	36(3)	32(4)	-(-)	56(5)	51(6)	2(T)	-(-)	-(-)	7(1)	-(-)
VERATRUM CALIFORNICUM	1(10)	-(-)	1(T)	-(-)	-(-)	2(2)	-(-)	-(-)	-(-)	-(-)	-(-)
VICIA AMERICANA	28(6)	36(2)	38(6)	8(10)	38(2)	38(6)	30(10)	57(5)	17(T)	33(8)	1(T)
VIGUIERA MULTIFLORA	5(2)	-(-)	5(T)	-(-)	6(T)	12(5)	8(T)	-(-)	-(-)	3(3)	1(T)
VIOLA ADUNCA	12(1)	9(2)	16(1)	17(1)	13(T)	11(1)	7(4)	-(-)	25(4)	13(1)	4(T)
VIOLA CANADENSIS	3(2)	-(-)	-(-)	-(-)	13(2)	3(3)	8(1)	-(-)	-(-)	( )	-(-)
VIOLA NUTTALLII	9(1)	9(T)	10(2)	8(T)	31(2)	9(1)	-(-)	-(-)	8(T)	3(3)	4(2)

APPENDIX A. (Con.)

	POTR/ JUCO/ SIHY C.T.	POTR/ JUCO/ ASMI C.T.	POTR/ VECA C.T.	POTR/ HELA C.T.	POTR/ PTAQ C.T.	POTR/ SESE C.T.	POTR/ CAGE C.T.	POTR/ FETH C.T.	POTR/ SIHY C.T.	POTR/ BRCA C.T.	POTR/ POPR C.T.
Number of Stands:	21	10	2	14	13	125	49	14	11	14	18
TREES											
ABIES CONCOLOR	5(T)	-(-)	-(-)	7(T)	-( )	2(4)	4(T)	14(T)	-(-)	7(T)	6(1)
ABIES LASIOCARPA	-(-)	10(T)	-(-)	7(T)	8(1)	30(1)	41(.)	36(1)	18(T)	21(T)	28(1)
PICEA ENGELMANNII	5(2)	10(T)	-(-)	-(-)	-(-)	7(1)	20(1)	29(3)	18(T)	-(-)	-(-)
PICEA PUNGENS	19(3)	-(-)	-(-)	-(-)	-(-)	2(T)	2(T)	-(-)	-(-)	7(T)	11(2)
PINUS CONTORTA	19(2)	40(3)	50(T)	-(-)	-(-)	1(1)	18(2)	-(-)	9(T)	21(T)	-(-)
PINUS FLEXILIS	5(2)	10(T)	-(-)	(-)	8(2)	1(T)	8(1)	-(-)	9(T)	14(2)	11(1)
PINUS PONDEROSA	14(2)	-(-)	-(-)	-(-)	-(-)	-(-)	2(1)	7(T)	55(3)	-(-)	11(1)
POPULUS TREMULOIDES	100(68)	100(79)	100(71)	100(83)	100(84)	100(78)	100(82)	100(78)	100(87)	100(73)	100(74)
PSEUDOTSUGA MENZIESII	29(2)	20(T)	-(-)	-(-)	8(1)	8(2)	14(T)	(-)	18(1)	14(T)	6(5)
SHRUBS											
ACER GLABRUM	-(-)	-(-)	-(-)	-(-)	8(2)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
ACER GRANDIDENTATUM	-(-)	-(-)	50(T)	7(T)	23(3)	8(2)	4(T)	-(-)	-(-)	-(-)	-(-)
AMELANCHIER ALNIFOLIA	19(T)	30(T)	-(-)	-(-)	31(T)	10(1)	16(1)	(-)	9(T)	7(1)	33(1)
ARCTOSTAPHYLOS UVA-URSI	19(1)	40(11)	(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
ARTEMISIA TRIDENTATA	71(9)	50(7)	-( )	-(-)	-(-)	4(2)	10(1)	-(-)	27(T)	-(-)	6(T)
BERBERIS REPENS	48(8)	70(12)	50(T)	-(-)	8(15)	13(3)	45(6)	(-)	36(2)	29(3)	61(2)
CEANOTHUS VELUTINUS	-(-)	(-)	-(-)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	7(3)	6(T)
CHRYSOTHAMNUS VISCIDIFLORUS	-(-)	(-)	-(-)	( )	-(-)	-(-)	6(T)	-(-)	-(-)	-(-)	-(-)
JUNIPERUS COMMUNIS	67(14)	100(17)	-(-)	-(-)	8(T)	1(T)	41(1)	-(-)	45(2)	21(2)	33(2)
PACHISTIMA MYRSINITES	-(-)	10(T)	-(-)	-(-)	-(-)	4(2)	10(1)	-(-)	-(-)	7(4)	-(-)
PHYSOCARPUS MALVACEUS	-(-)	-(-)	-(-)	-(-)	-(-)	1(T)	-(-)	-(-)	(-)	-(-)	-(-)
PRUNUS VIRGINIANA	-(-)	( )	-( )	7(T)	8(T)	9(2)	2(2)	-(-)	-(-)	7(T)	17(T)
QUERCUS GAMBELII	5(T)	-(-)	-(-)	-(-)	-(-)	1(2)	2(T)	-(-)	-(-)	-(-)	17(1)
RIBES LACUSTRE	-(-)	(-)	-(-)	(-)	-(-)	2(2)	-(-)	7(2)	-(-)	14(2)	-(-)
RIBES MONTIGENUM	-(-)	-(-)	-(-)	-(-)	-(-)	8(2)	2(T)	-(-)	-(-)	-(-)	-(-)
RIBES SP.	-(-)	-(-)	50(T)	7(T)	-(-)	6(1)	12(T)	-(-)	-(-)	-(-)	22(T)
ROSA WOODSII	33(1)	60(3)	50(T)	14(3)	8(T)	12(1)	51(T)	36(1)	27(T)	14(T)	44(2)
RUBUS PARVIFLORUS	-(-)	-(-)	-(-)	-(-)	8(2)	2(T)	-(-)	-(-)	-(-)	-(-)	-(-)
SALIX SCOULERIANA	-(-)	-(-)	-(-)	7(3)	8(5)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
SAMBUCUS RACEMOSA	-(-)	-(-)	-(-)	57(1)	46(1)	35(1)	2(T)	-(-)	-(-)	14(3)	6(T)
SHEPHERDIA CANADENSIS	-(-)	-(-)	-(-)	(-)	-(-)	2(T)	2(T)	-(-)	-(-)	-(-)	6(1)
SORBUS SCOPULINA	-(-)	-(-)	-(-)	-(-)	-(-)	2(2)	-(-)	-(-)	-(-)	-(-)	-(-)
SYMPHORICARPOS OREOPHILUS	62(19)	70(7)	50(T)	64(3)	54(4)	59(2)	69(3)	79(2)	45(1)	64(2)	78(3)
VACCINIUM CAESPITOSUM	-(-)	-( )	-(-)	-(-)	-(-)	-(-)	4(T)	-(-)	-(-)	-(-)	-(-)
VACCINIUM SCOPARIUM	-(-)	-(-)	-(-)	-( )	-(-)	1(T)	2(T)	-(-)	-(-)	-(-)	-(-)
GRAMINOIDS											
AGROPYRON TRACHYCAULUM	38(3)	70(6)	100(5)	36(2)	23(3)	67(5)	61(6)	57(1)	18(1)	64(13)	56(6)
ARRHENATHERUM ELATIUS	-(-)	-(-)	50(T)	-(-)	-(-)	1(1)	-(-)	7(20)	-(-)	-(-)	-(-)
BROMUS ANOMALUS	33(4)	-(-)	-(-)	-(-)	-( )	2(1)	12(3)	21(4)	9(10)	-(-)	6(5)
BROMUS CARINATUS	10(3)	-(-)	50(4)	86(12)	69(6)	82(16)	27(5)	21(20)	-(-)	100(31)	44(2)
BROMUS CILIATUS	-(-)	60(2)	-(-)	7(3)	8(4)	5(2)	27(2)	14(3)	18(5)	-(-)	6(10)
CALAMAGROSTIS RUBESCENS	-(-)	-(-)	-(-)	-(-)	-(-)	1(4)	2(75)	-(-)	-(-)	-(-)	6(2)
CAREX GEYERI	-(-)	20(1)	-(-)	-(-)	-(-)	6(3)	51(22)	7(T)	9(T)	14(1)	6(T)
CAREX HOODII	-(-)	-( )	50(7)	21(1)	8(T)	24(3)	6(5)	7(T)	-(-)	7(T)	-(-)
CAREX OBTUSATA	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	8(14)	21(7)	9(1)	-(-)	-(-)
CAREX ROSSII	19(1)	-(-)	-(-)	-(-)	15(2)	3(1)	31(10)	14(2)	9(4)	7(1)	11(T)
DACTYLIS GLOMERATA	-(-)	-(-)	50(3)	-(-)	-(-)	8(2)	2(T)	-(-)	-(-)	21(3)	22(22)
ELYMUS CINEREUS	-(-)	-(-)	-(-)	-(-)	-(-)	2(1)	-(-)	-(-)	-(-)	-(-)	-(-)
ELYMUS GLAUCUS	-(-)	10(T)	-(-)	50(6)	69(11)	46(17)	18(5)	-(-)	-(-)	36(14)	11(4)
FESTUCA IDAHOENSIS	10(8)	-(-)	-(-)	-(-)	-(-)	2(1)	6(3)	7(T)	9(T)	7(2)	11(T)
FESTUCA THURBERI	5(T)	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	100(18)	9(T)	-(-)	-(-)
KOELERIA CRISTATA	19(1)	10(10)	-(-)	-(-)	-(-)	2(10)	4(T)	-(-)	9(T)	-(-)	-(-)
LEUCOPOA KINGII	14(4)	60(6)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
MELICA SPECTABILIS	-(-)	-(-)	-(-)	7(2)	8(T)	19(1)	14(2)	-(-)	-(-)	21(2)	22(1)
PHLEUM ALPINUM	-(-)	-(-)	50(5)	-(-)	-(-)	5(2)	4(1)	-(-)	-(-)	7(5)	-(-)
POA FENDLERIANA	24(14)	-(-)	-(-)	-(-)	-(-)	-(-)	27(1)	21(1)	73(6)	-(-)	11(2)
POA NERVOSA	5(1)	-(-)	-(-)	21(2)	23(1)	37(1)	14(3)	-(-)	-(-)	21(T)	6(10)
POA PRATENSIS	29(4)	-(-)	50(3)	7(4)	23(3)	26(17)	35(9)	43(5)	9(T)	43(9)	100(37)
SITANION HYSTRIX	48(4)	-(-)	-(-)	-(-)	-(-)	-(-)	20(1)	36(1)	91(10)	-(-)	6(T)
STIPA COMATA	57(12)	10(T)	-(-)	-(-)	-(-)	-(-)	4(T)	21(1)	73(17)	-(-)	6(3)
STIPA LETTERMANII	43(6)	-(-)	-(-)	-(-)	-(-)	5(1)	20(4)	7(7)	9(4)	7(1)	11(T)
STIPA OCCIDENTALIS	19(1)	20(T)	-(-)	-(-)	8(T)	19(3)	53(19)	71(2)	9(5)	14(T)	17(T)
TRISETUM SPICATUM	-(-)	-(-)	-(-)	7(1)	-(-)	7(T)	27(1)	29(T)	9(T)	21(T)	6(T)

APPENDIX A. (Con.)

	POTR/ JUCO/ SIHY C.T.	POTR/ JUCO/ ASMI C.T.	POTR/ VECA C.T.	POTR/ HELA C.T.	POTR/ PTAQ C.T.	POTR/ SESE C.T.	POTR/ CAGE C.T.	POTR/ FETH C.T.	POTR/ SIHY C.T.	POTR/ BRCA C.T.	POTR/ POPR C.T.
Number of Stands:	21	10	2	14	13	125	49	14	11	14	18
FORBS											
ACHILLEA MILLEFOLIUM	52(2)	90(2)	100(T)	7(3)	15(2)	57(2)	59(2)	64(3)	9(3)	64(2)	72(2)
ACTAEA RUBRA	-(-)	-(-)	-(-)	29(5)	31(9)	5(1)	-(-)	-(-)	-(-)	-(-)	-(-)
AGASTACHE URTICIFOLIA	-(-)	-(-)	-(-)	57(2)	62(7)	42(4)	2(T)	7(T)	-(-)	14(T)	6(T)
AGOSERIS GLAUCA	5(T)	30(T)	-(-)	7(T)	-(-)	4(T)	8(T)	7(T)	18(T)	7(T)	6(T)
ALLIUM BREVISTYLUM	-(-)	10(T)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	-(-)	-(-)
ALLIUM CERNUUM	14(T)	20(1)	-(-)	-(-)	-(-)	-(-)	2(1)	-(-)	9(T)	-(-)	-(-)
ANTENNARIA MICROPHYLLA	38(5)	60(2)	-(-)	7(7)	-(-)	1(T)	20(1)	21(T)	64(3)	-(-)	-(-)
ANTENNARIA PARVIFOLIA	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
APOCYNUM ANDROSAEMIFOLIUM	5(T)	-(-)	-(-)	-(-)	-(-)	1(T)	2(T)	-(-)	-(-)	-(-)	-(-)
AQUILEGIA COERULEA	5(T)	20(T)	-(-)	7(3)	8(T)	18(T)	16(1)	14(T)	-(-)	29(T)	-(-)
ARENARIA CONGESTA	10(1)	10(T)	-(-)	-(-)	-(-)	1(2)	-(-)	-(-)	9(T)	-(-)	-(-)
ARNICA CORDIFOLIA	-(-)	10(T)	-(-)	-(-)	-(-)	3(1)	6(1)	-(-)	9(1)	-(-)	-(-)
ARNICA LATIFOLIA	-(-)	30(4)	-(-)	-(-)	-(-)	1(T)	4(5)	-(-)	-(-)	-(-)	6(T)
ARTEMISIA LUDOVICIANA	-(-)	-(-)	-(-)	-(-)	-(-)	4(2)	-(-)	-(-)	-(-)	-(-)	-(-)
ASTER CHILENSIS	5(2)	-(-)	-(-)	-(-)	-(-)	3(T)	4(T)	-(-)	-(-)	-(-)	-(-)
ASTER ENGELMANNII	-(-)	-(-)	-(-)	50(3)	54(1)	22(3)	2(T)	-(-)	-(-)	-(-)	6(T)
ASTER FOLIACEUS	-(-)	-(-)	100(T)	7(3)	-(-)	6(6)	-(-)	-(-)	-(-)	-(-)	11(3)
ASTER OCCIDENTALIS	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	14(4)	-(-)
ASTRAGALUS MISER	19(5)	100(18)	-(-)	-(-)	-(-)	2(1)	31(17)	-(-)	18(4)	-(-)	22(2)
CAMPANULA ROTUNDIFOLIA	5(T)	10(T)	-(-)	-(-)	-(-)	-(-)	4(T)	-(-)	-(-)	-(-)	-(-)
CASTILLEJA MINIATA	10(T)	20(T)	-(-)	7(T)	8(T)	7(1)	12(T)	7(T)	9(2)	14(T)	-(-)
CHENOPODIUM FREMONTII	5(T)	-(-)	-(-)	21(2)	8(3)	11(3)	2(T)	7(T)	9(T)	14(T)	-(-)
CHLOROCRAMBE HASTATA	-(-)	-(-)	-(-)	14(T)	31(4)	2(T)	-(-)	-(-)	-(-)	-(-)	-(-)
CIRCAEA ALPINA	-(-)	-(-)	-(-)	7(T)	15(25)	2(5)	-(-)	-(-)	-(-)	-(-)	-(-)
CIRSIUM ARVENSE	19(T)	-(-)	-(-)	-(-)	8(T)	1(T)	2(T)	7(T)	9(T)	7(T)	6(T)
CIRSIUM VULGARE	-(-)	-(-)	50(T)	-(-)	-(-)	1(T)	4(T)	-(-)	-(-)	-(-)	6(T)
CLEMATIS COLUMBIANA	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	-(-)
COLLINSIA PARVIFLORA	-(-)	-(-)	-(-)	-(-)	15(4)	19(8)	6(T)	-(-)	-(-)	7(T)	17(1)
COLLOMIA LINEARIS	-(-)	-(-)	-(-)	7(T)	15(T)	33(5)	4(2)	7(T)	-(-)	21(1)	6(2)
CORALLORHIZA MACULATA	-(-)	-(-)	-(-)	-(-)	-(-)	1(T)	4(T)	21(T)	9(T)	7(T)	6(T)
DELPHINIUM NUTTALLIANUM	5(T)	10(T)	-(-)	-(-)	15(T)	11(T)	6(T)	-(-)	-(-)	-(-)	22(1)
DELPHINIUM OCCIDENTALE	-(-)	-(-)	-(-)	43(2)	31(T)	33(4)	-(-)	7(T)	-(-)	14(T)	6(T)
DESCURAINIA CALIFORNICA	-(-)	-(-)	-(-)	-(-)	8(T)	9(2)	2(T)	-(-)	-(-)	-(-)	-(-)
DESCURAINIA RICHARDSONII	-(-)	-(-)	-(-)	57(3)	62(1)	53(1)	14(1)	29(1)	9(T)	29(1)	11(T)
EPILOBIUM ANGUSTIFOLIUM	-(-)	-(-)	-(-)	-(-)	-(-)	5(T)	4(T)	7(T)	-(-)	-(-)	6(1)
ERIGERON FLAGELLARIS	-(-)	-(-)	-(-)	-(-)	8(1)	-(-)	6(1)	-(-)	-(-)	-(-)	-(-)
ERIGERON PEREGRINUS	5(T)	40(T)	-(-)	-(-)	-(-)	-(-)	2(3)	-(-)	-(-)	7(1)	-(-)
ERIGERON SPECIOSUS	10(1)	10(T)	100(T)	-(-)	8(1)	14(1)	12(3)	-(-)	9(1)	7(T)	22(1)
ERIGERON URSINUS	-(-)	-(-)	-(-)	-(-)	-(-)	1(3)	-(-)	-(-)	-(-)	-(-)	6(T)
ERYTHRONIUM GRANDIFLORUM	-(-)	-(-)	-(-)	-(-)	-(-)	3(1)	4(3)	-(-)	-(-)	-(-)	-(-)
FRAGARIA VESCA	10(3)	10(5)	-(-)	7(5)	8(T)	10(4)	29(2)	14(1)	-(-)	7(T)	33(T)
FRASERA SPECIOSA	14(1)	10(T)	-(-)	-(-)	-(-)	6(2)	18(2)	-(-)	-(-)	-(-)	6(3)
GALIUM APARINE	-(-)	-(-)	50(T)	-(-)	-(-)	-(-)	2(4)	-(-)	-(-)	-(-)	-(-)
GALIUM BIFOLIUM	-(-)	-(-)	-(-)	50(1)	31(10)	27(5)	6(13)	-(-)	9(T)	-(-)	11(T)
GALIUM BOREALE	10(T)	50(2)	50(T)	7(T)	23(3)	10(3)	22(1)	-(-)	-(-)	14(T)	17(2)
GERANIUM RICHARDSONII	-(-)	-(-)	-(-)	21(T)	15(3)	10(5)	4(2)	-(-)	-(-)	-(-)	6(T)
GERANIUM VISCOSISSIMUM	38(1)	70(T)	-(-)	14(14)	-(-)	24(4)	41(6)	7(T)	-(-)	14(T)	39(1)
HABENARIA UNALASCENSIS	-(-)	10(T)	-(-)	-(-)	-(-)	1(T)	2(T)	-(-)	-(-)	-(-)	-(-)
HACKELIA FLORIBUNDA	5(T)	-(-)	-(-)	14(5)	54(1)	42(3)	16(4)	-(-)	-(-)	36(2)	6(T)
HAPLOPAPPUS PARRYI	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	6(1)	14(T)	-(-)	-(-)	-(-)
HELENIUM HOOPESII	-(-)	-(-)	50(T)	7(3)	-(-)	7(2)	10(2)	29(T)	9(T)	21(4)	17(4)
HELIANTHELLA UNIFLORA	-(-)	-(-)	-(-)	-(-)	-(-)	2(22)	-(-)	-(-)	-(-)	-(-)	-(-)
HERACLEUM LANATUM	-(-)	-(-)	-(-)	100(20)	23(3)	6(T)	-(-)	-(-)	-(-)	-(-)	-(-)
HIERACIUM ALBIFLORUM	-(-)	-(-)	-(-)	-(-)	-(-)	1(T)	2(T)	-(-)	-(-)	7(T)	-(-)
HYDROPHYLLUM CAPITATUM	-(-)	-(-)	-(-)	7(T)	15(1)	19(1)	-(-)	-(-)	-(-)	-(-)	11(T)
HYDROPHYLLUM FENDLERI	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	2(2)	-(-)	-(-)	-(-)	-(-)
IRIS MISSOURIENSIS	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	4(5)	-(-)	-(-)	-(-)	28(10)
LATHYRUS ARIZONICUS	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	14(38)	-(-)	-(-)	-(-)
LATHYRUS LANSZWERTII	5(T)	-(-)	-(-)	43(13)	31(18)	44(13)	27(28)	36(41)	9(4)	57(21)	-(-)
LATHYRUS LEUCANTHUS	-(-)	-(-)	-(-)	21(10)	8(10)	14(14)	14(21)	36(36)	-(-)	14(17)	11(4)
LATHYRUS PAUCIFLORUS	-(-)	-(-)	-(-)	-(-)	-(-)	10(1)	-(-)	-(-)	-(-)	-(-)	-(-)
LIGUSTICUM FILICINUM	-(-)	-(-)	-(-)	-(-)	-(-)	5(11)	4(3)	-(-)	-(-)	-(-)	-(-)
LIGUSTICUM PORTERI	5(T)	-(-)	-(-)	7(T)	-(-)	2(1)	27(1)	14(1)	-(-)	14(3)	11(1)
LUPINUS ARGENTEUS	48(21)	40(2)	-(-)	-(-)	-(-)	9(4)	24(13)	7(T)	36(19)	7(25)	28(5)
LUPINUS CAUDATUS	5(30)	-(-)	-(-)	-(-)	-(-)	1(10)	2(1)	-(-)	-(-)	-(-)	-(-)

APPENDIX A. (Con.)

	POTR/ JUCO/ SIHY C.T.	POTR/ JUCO/ ASMI C.T.	POTR/ VECA C.T.	POTR/ HELA C.T.	POTR/ PTAQ C.T.	POTR/ SESE C.T.	POTR/ CAGE C.T.	POTR/ FETH C.T.	POTR/ SIHY C.T.	POTR/ BRCA C.T.	POTR/ POPR C.T.
Number of Stands:	21	10	2	14	13	125	49	14	11	14	18
FORBS (CONT'D)											
MERTENSIA ARIZONICA	-(-)	-(-)	-(-)	43(5)	15(1)	43(14)	4(T)	7(T)	-(-)	7(T)	11(T)
MERTENSIA CILIATA	-(-)	-(-)	-(-)	-(-)	-(-)	2(25)	-(-)	-(-)	-(-)	-(-)	-(-)
MERTENSIA FRANCISCANA	-(-)	-(-)	-(-)	7(10)	-(-)	1(20)	2(T)	-(-)	-(-)	-(-)	-(-)
MERTENSIA LONGIFLORA	-(-)	-(-)	-(-)	-(-)	-(-)	2(17)	-(-)	-(-)	(-)	-(-)	-(-)
NEMOPHILA BREVIFLORA	-(-)	-(-)	-(-)	43(21)	46(5)	42(21)	2(20)	-(-)	-(-)	7(15)	-(-)
OSMORHIZA CHILENSIS	-(-)	-(-)	50(T)	36(6)	46(4)	43(3)	22(3)	21(2)	-(-)	29(2)	44(3)
OSMORHIZA OCCIDENTALIS	-(-)	-(-)	-(-)	29(2)	-(-)	37(3)	2(T)	-(-)	(-)	14(T)	11(T)
PEDICULARIS RACEMOSA	-(-)	(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	(-)	-(-)	-(-)
PENSTEMON PROCERUS	-(-)	-(-)	-(-)	-(-)	-(-)	2(T)	2(20)	7(T)	-(-)	7(T)	-(-)
PENSTEMON RYDBERGII	-(-)	-(-)	-(-)	-(-)	(-)	6(2)	6(1)	-(-)	-(-)	-(-)	6(T)
PHACELIA HETEROPHYLLA	-(-)	(-)	-(-)	21(5)	31(1)	16(3)	6(T)	-(-)	9(T)	7(T)	-(-)
POLEMONIUM FOLIOSISSIMUM	-(-)	-(-)	-(-)	57(6)	38(1)	37(3)	4(T)	-(-)	-(-)	-(-)	-(-)
POLYGONUM DOUGLASII	10(T)	-(-)	-(-)	14(T)	23(T)	36(6)	10(T)	7(T)	18(T)	36(3)	6(T)
POTENTILLA DIVERSIFOLIA	14(7)	(-)	-(-)	-(-)	-(-)	-(-)	2(T)	7(T)	9(2)	-(-)	-(-)
POTENTILLA GLANDULOSA	5(T)	-(-)	-(-)	-(-)	8(T)	9(1)	6(T)	29(T)	18(T)	-(-)	-(-)
POTENTILLA GRACILIS	-(-)	30(T)	-(-)	7(T)	-(-)	7(1)	27(1)	43(T)	18(T)	21(T)	11(1)
PTERIDIUM AQUILINUM	-(-)	-(-)	-(-)	7(T)	100(51)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
RANUNCULUS INAMOENUS	-(-)	-(-)	-(-)	7(T)	-(-)	5(T)	16(T)	7(T)	( )	21(1)	11(T)
RUDBECKIA OCCIDENTALIS	-(-)	-(-)	100(3)	93(14)	92(8)	70(15)	6(20)	-(-)	-(-)	43(8)	28(1)
SCROPHULARIA LANCEOLATA	-(-)	-(-)	-(-)	50(1)	38(1)	22(2)	2(T)	-(-)	-( )	7(T)	-(-)
SENECIO CYMBALARIOIDES	-(-)	30(T)	-(-)	7(T)	8(T)	16(1)	14(1)	-(-)	-(-)	14(T)	-(-)
SENECIO INTEGERRIMUS	5(T)	-(-)	-(-)	-(-)	-(-)	2(2)	4(T)	-(-)	9(T)	-(-)	6(T)
SENECIO SERRA	-(-)	-(-)	-(-)	71(5)	46(4)	50(4)	-(-)	-(-)	-(-)	-(-)	-(-)
SENECIO VULGARIS	5(T)	-(-)	-(-)	-(-)	-(-)	1(T)	4(T)	29(T)	9(T)	-(-)	6(T)
SIDALCEA OREGANA	-(-)	-(-)	50(3)	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	-(-)	11(T)
SILENE MENZIESII	10(T)	-(-)	-(-)	7(T)	8(T)	6(1)	4(2)	7(T)	-(-)	7(T)	-(-)
SMILACINA RACEMOSA	-(-)	-(-)	-(-)	7(T)	8(T)	3(4)	4(T)	-(-)	-(-)	-(-)	-(-)
SMILACINA STELLATA	10(T)	50(T)	50(3)	36(3)	46(12)	8(3)	24(2)	14(T)	-(-)	14(2)	22(1)
STELLARIA JAMESIANA	-(-)	10(2)	50(T)	36(2)	38(2)	73(4)	18(5)	21(5)	-(-)	50(1)	22(2)
TARAXACUM OFFICINALE	71(5)	70(3)	50(10)	14(2)	8(T)	28(3)	57(5)	79(8)	91(2)	50(17)	89(5)
THALICTRUM FENDLERI	10(5)	50(3)	-(-)	50(21)	46(4)	55(7)	31(3)	-(-)	9(T)	64(6)	39(1)
THERMOPSIS MONTANA	-(-)	10(25)	-(-)	-(-)	-(-)	-(-)	6(3)	-(-)	-(-)	7(T)	22(1)
TRAGOPOGON DUBIUS	10(T)	-(-)	50(T)	-(-)	8(T)	6(T)	4(T)	-(-)	9(T)	7(T)	-(-)
TRIFOLIUM LONGIPES	5(10)	10(3)	50(10)	-(-)	-(-)	5(9)	10(8)	7(T)	9(T)	-(-)	22(3)
URTICA DIOICA	-(-)	-(-)	-(-)	21(T)	23(2)	6(1)	-(-)	-(-)	-(-)	-(-)	6(T)
VALERIANA OCCIDENTALIS	-(-)	-(-)	50(T)	71(11)	31(3)	55(5)	-(-)	-(-)	-(-)	-(-)	6(T)
VERATRUM CALIFORNICUM	-(-)	-(-)	100(42)	-(-)	-(-)	2(3)	2(T)	-(-)	-(-)	(-)	-(-)
VICIA AMERICANA	-(-)	-(-)	50(3)	50(5)	15(1)	41(7)	16(1)	71(7)	9(1)	50(2)	39(6)
VIGUIERA MULTIFLORA	-(-)	10(5)	-(-)	-(-)	8(T)	6(1)	2(T)	-(-)	-(-)	21(T)	-(-)
VIOLA ADUNCA	-(-)	-(-)	-(-)	-(-)	(-)	12(1)	14(2)	-(-)	-(-)	14(T)	33(1)
VIOLA CANADENSIS	-(-)	-(-)	-(-)	-(-)	-(-)	2(1)	4(T)	-(-)	-(-)	-(-)	-(-)
VIOLA NUTTALLII	-(-)	-(-)	-(-)	-(-)	15(T)	18(2)	2(T)	-(-)	-(-)	29(1)	11(1)

APPENDIX A. (Con.)

	POTR-ABLA/ VACA C.T.	POTR-ABLA/ AMAL C.T.	POTR-ABLA/ SYOR/ SESE C.T.	POTR-ABLA/ SYOR/ CAGE C.T.	POTR-ABLA/ JUCO C.T.	POTR-ABLA/ SESE C.T.	POTR-ABLA/ CAGE C.T.	POTR-ABCO/ SYOR C.T.	POTR-ABCO/ JUCO C.T.	POTR-PSME/ AMAL C.T.	POTR-PSME/ JUCO C.T.
Number of Stands:	4	13	48	14	34	94	77	27	20	10	8
TREES											
ABIES CONCOLOR	-(-)	8(10)	4(3)	7(T)	3(10)	2(6)	3(20)	96(20)	75(19)	20(1)	-(-)
ABIES LASIOCARPA	100(29)	100(18)	98(13)	86(20)	88(16)	100(18)	92(24)	7(1)	10(T)	40(2)	25(1)
PICEA ENGELMANNII	25(T)	31(10)	13(5)	36(14)	50(7)	24(6)	57(13)	-(-)	-(-)	-(-)	13(T)
PICEA PUNGENS	-(-)	-(-)	2(10)	21(3)	15(12)	1(3)	5(9)	11(16)	55(20)	-(-)	13(5)
PINUS CONTORTA	100(17)	8(8)	4(2)	14(7)	15(7)	5(12)	8(8)	-(-)	-(-)	-(-)	38(13)
PINUS FLEXILIS	-(-)	(-)	-(-)	14(T)	41(3)	1(T)	17(2)	4(T)	30(4)	-(-)	13(5)
PINUS PONDEROSA	-(-)	-(-)	-(-)	-(-)	15(3)	-(-)	4(T)	-(-)	15(2)	-(-)	13(25)
POPULUS TREMULOIDES	100(47)	100(67)	100(67)	100(74)	100(67)	100(68)	100(63)	100(60)	100(65)	100(66)	100(59)
PSEUDOTSUGA MENZIESII	-(-)	31(3)	25(1)	36(4)	44(4)	9(5)	13(4)	22(7)	75(8)	100(18)	100(18)
SHRUBS											
ACER GLABRUM	-(-)	-(-)	2(T)	-(-)	-(-)	1(T)	-(-)	-(-)	-(-)	10(3)	-(-)
ACER GRANDIDENTATUM	-(-)	38(4)	-(-)	-(-)	-(-)	4(1)	-(-)	15(1)	-(-)	40(35)	-(-)
AMELANCHIER ALNIFOLIA	-(-)	92(9)	15(1)	14(6)	15(2)	14(1)	8(T)	26(1)	20(T)	90(20)	25(3)
ARCTOSTAPHYLOS UVA-URSI	-(-)	-(-)	-(-)	-(-)	3(T)	-(-)	-(-)	4(T)	10(T)	-(-)	13(T)
ARTEMISIA TRIDENTATA	-(-)	8(1)	6(1)	-(-)	3(T)	4(T)	1(1)	-(-)	10(4)	10(T)	38(1)
BERBERIS REPENS	50(1)	69(4)	25(3)	50(3)	56(2)	17(1)	30(3)	48(8)	55(9)	70(15)	88(8)
CEANOTHUS VELUTINUS	-(-)	8(T)	-(-)	-(-)	-(-)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
CHRYSOTHAMNUS VISCIDIFLORUS	-(-)	8(1)	-(-)	-(-)	9(1)	-(-)	1(T)	-(-)	15(1)	-(-)	-(-)
JUNIPERUS COMMUNIS	-(-)	-(-)	6(2)	21(1)	100(12)	-(-)	31(1)	7(3)	100(11)	-(-)	100(18)
PACHISTIMA MYRSINITES	50(5)	69(17)	15(2)	7(T)	9(3)	14(1)	8(1)	26(1)	-(-)	70(2)	13(5)
PHYSOCARPUS MALVACEUS	-(-)	23(23)	4(38)	-(-)	-(-)	-(-)	-(-)	4(T)	-(-)	40(1)	-(-)
PRUNUS VIRGINIANA	-( )	54(14)	13(1)	-(-)	6(T)	6(1)	1(T)	11(T)	-(-)	40(5)	-(-)
QUERCUS GAMBELII	-(-)	15(15)	-(-)	7(3)	-(-)	-(-)	-(-)	4(5)	-(-)	20(1)	-(-)
RIBES LACUSTRE	-(-)	8(3)	-(-)	7(T)	-(-)	1(T)	1(T)	-(-)	-(-)	-(-)	-(-)
RIBES MONTIGENUM	-(-)	-(-)	6(T)	-(-)	3(2)	16(3)	6(T)	4(T)	-(-)	-(-)	-(-)
RIBES SP.	25(T)	-(-)	8(T)	-(-)	9(2)	12(1)	3(T)	-(-)	-(-)	30(1)	-(-)
ROSA WOODSII	50(2)	62(2)	31(1)	57(3)	53(T)	16(T)	18(T)	59(1)	20(T)	90(T)	63(T)
RUBUS PARVIFLORUS	50(1)	-(-)	8(23)	-(-)	-(-)	5(1)	-(-)	-(-)	-(-)	10(3)	13(T)
SALIX SCOULERIANA	-(-)	8(T)	6(1)	-(-)	-(-)	6(1)	-(-)	-(-)	-(-)	60(2)	-(-)
SAMBUCUS RACEMOSA	-(-)	8(T)	21(2)	-(-)	-(-)	23(2)	1(T)	7(T)	-(-)	-(-)	-(-)
SHEPHERDIA CANADENSIS	25(T)	23(7)	6(1)	-(-)	6(T)	3(1)	3(1)	-(-)	-(-)	10(4)	13(1)
SORBUS SCOPULINA	-(-)	31(2)	13(1)	-(-)	-(-)	1(T)	-(-)	-(-)	-(-)	30(2)	-(-)
SYMPHORICARPOS OREOPHILUS	-(-)	100(25)	96(32)	100(33)	53(4)	57(2)	31(1)	100(27)	70(3)	100(21)	88(11)
VACCINIUM CAESPITOSUM	75(15)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
VACCINIUM SCOPARIUM	75(9)	-(-)	2(T)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
GRAMINOIDS											
AGROPYRON TRACHYCAULUM	75(3)	46(5)	65(7)	57(9)	41(3)	57(5)	38(4)	48(1)	50(2)	40(6)	63(3)
ARRHENATHERUM ELATIUS	-(-)	-(-)	-(-)	-(-)	-(-)	1(3)	-(-)	11(10)	-(-)	-(-)	-(-)
BROMUS ANOMALUS	-(-)	-(-)	-(-)	14(5)	41(4)	5(11)	22(5)	15(4)	50(5)	-(-)	13(3)
BROMUS CARINATUS	-(-)	31(2)	67(9)	36(1)	9(4)	64(11)	13(1)	48(3)	15(2)	40(24)	13(T)
BROMUS CILIATUS	-(-)	23(T)	8(1)	14(4)	35(1)	12(4)	16(5)	11(3)	5(1)	-(-)	38(1)
CALAMAGROSTIS RUBESCENS	-(-)	-(-)	-(-)	-(-)	-(-)	1(38)	1(T)	-(-)	-(-)	10(T)	-(-)
CAREX GEYERI	25(10)	31(11)	17(6)	71(17)	15(22)	10(10)	14(13)	11(1)	10(4)	20(34)	38(12)
CAREX HOODII	-(-)	8(T)	35(3)	7(7)	3(T)	33(4)	3(13)	7(2)	-(-)	10(10)	-(-)
CAREX OBTUSATA	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	4(13)	-(-)	-(-)	-(-)	-(-)
CAREX ROSSII	-(-)	15(T)	6(T)	29(10)	56(6)	15(1)	69(3)	-(-)	30(2)	-(-)	25(8)
DACTYLIS GLOMERATA	-(-)	-(-)	6(2)	-(-)	-(-)	6(T)	4(T)	33(7)	5(T)	-(-)	-(-)
ELYMUS CINEREUS	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
ELYMUS GLAUCUS	25(2)	69(3)	50(5)	14(2)	12(14)	39(12)	3(T)	37(10)	-(-)	70(12)	-(-)
FESTUCA IDAHOENSIS	-(-)	-(-)	2(2)	7(T)	3(3)	-(-)	1(1)	-(-)	5(T)	-(-)	13(T)
FESTUCA THURBERI	-(-)	8(17)	2(T)	29(5)	-(-)	2(10)	10(1)	-(-)	-(-)	10(T)	13(10)
KOELERIA CRISTATA	25(3)	-(-)	2(T)	-(-)	6(T)	-(-)	8(1)	-(-)	5(T)	-(-)	-(-)
LEUCOPOA KINGII	-(-)	-(-)	-(-)	-(-)	-(-)	1(1)	1(T)	-(-)	-(-)	-(-)	-(-)
MELICA SPECTABILIS	-(-)	15(T)	10(1)	-(-)	-(-)	16(2)	9(2)	7(1)	-(-)	-(-)	-(-)
PHLEUM ALPINUM	-(-)	( )	-(-)	-(-)	3(T)	6(1)	4(T)	-(-)	-(-)	-(-)	-(-)
POA FENDLERIANA	-(-)	-(-)	-(-)	-(-)	21(3)	1(T)	13(1)	-(-)	10(3)	-(-)	50(3)
POA NERVOSA	25(T)	15(T)	17(2)	-(-)	9(1)	30(3)	9(2)	-(-)	-(-)	10(T)	13(3)
POA PRATENSIS	-(-)	31(3)	29(21)	36(10)	32(14)	26(9)	10(11)	30(5)	40(13)	40(6)	25(13)
SITANION HYSTRIX	-(-)	-(-)	-(-)	7(1)	29(3)	1(T)	16(2)	-(-)	40(1)	-(-)	50(1)
STIPA COMATA	-(-)	-(-)	-(-)	-(-)	6(9)	-(-)	-(-)	-(-)	10(4)	-(-)	13(T)
STIPA LETTERMANII	-(-)	8(T)	6(1)	7(1)	26(1)	4(2)	17(2)	-(-)	-(-)	-(-)	13(3)
STIPA OCCIDENTALIS	-(-)	15(5)	19(5)	50(6)	53(4)	29(6)	42(3)	37(5)	80(7)	10(10)	63(6)
TRISETUM SPICATUM	-(-)	-(-)	6(T)	-(-)	12(5)	15(T)	21(T)	4(T)	5(T)	-(-)	13(T)

APPENDIX A. (Con.)

	POTR-ABLA/VACA C.T.	POTR-ABLA/AMAL C.T.	POTR-ABLA/SVOR/SESE C.T.	POTR-ABLA/SVOR/CAGE C.T.	POTR-ABLA/JUCO C.T.	POTR-ABLA/SESE C.T.	POTR-ABLA/CAGE C.T.	POTR-ABCO/SVOR C.T.	POTR-ABCO/JUCO C.T.	POTR-PSME/AMAL C.T.	POTR-PSME/JUCO C.T.
Number of Stands:	4	13	48	14	34	94	77	27	20	10	8
FORBS											
ACHILLEA MILLEFOLIUM	25(T)	54(1)	52(2)	86(1)	68(1)	66(3)	74(2)	48(1)	55(2)	50(1)	38(1)
ACTAEA RUBRA	-(-)	-(-)	2(T)	7(T)	-(-)	9(11)	-( )	7(T)	-(-)	10(T)	-(-)
AGASTACHE URTICIFOLIA	-(-)	23(5)	54(4)	-(-)	-(-)	29(2)	-(-)	30(3)	-(-)	30(7)	-(-)
AGOSERIS GLAUCA	-(-)	-(-)	4(T)	14(T)	6(T)	5(T)	10(T)	4(T)	10(T)	(-)	-(-)
ALLIUM BREVISTYLUM	-(-)	8(T)	2(T)	-(-)	-(-)	-(-)	1(T)	-(-)	-(-)	-(-)	-(-)
ALLIUM CERNUUM	-(-)	-(-)	-(-)	-(-)	6(T)	-(-)	-(-)	-(-)	-(-)	(-)	-(-)
ANTENNARIA MICROPHYLLA	-(-)	-(-)	4(T)	7(T)	18(3)	1(T)	13(T)	-(-)	10(8)	-(-)	13(T)
ANTENNARIA PARVIFOLIA	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	1(2)	-(-)	-(-)	-(-)	13(1)
APOCYNUM ANDROSAEMIFOLIUM	-(-)	8(3)	-(-)	-(-)	3(T)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
AQUILEGIA COERULEA	-(-)	23(1)	25(1)	14(T)	15(1)	37(T)	5(T)	22(1)	-(-)	10(T)	13(T)
ARENARIA CONGESTA	-(-)	-(-)	-( )	-(-)	6(1)	-(-)	1(T)	-(-)	-(-)	-(-)	-(-)
ARNICA CORDIFOLIA	-(-)	8(3)	10(2)	-(-)	9(4)	6(2)	14(2)	4(1)	10(8)	30(4)	13(3)
ARNICA LATIFOLIA	100(18)	-(-)	2(20)	-(-)	6(15)	3(7)	-(-)	-(-)	-(-)	-(-)	25(8)
ARTEMISIA LUDOVICIANA	-(-)	-(-)	-(-)	-(-)	-(-)	3(1)	1(T)	-(-)	-(-)	-(-)	13(T)
ASTER CHILENSIS	-(-)	8(T)	4(T)	7(2)	3(T)	1(T)	-(-)	7(T)	-(-)	10(T)	-(-)
ASTER ENGELMANNII	75(1)	62(6)	44(4)	-(-)	-(-)	48(1)	3(T)	41(2)	-(-)	40(T)	-(-)
ASTER FOLIACEUS	-(-)	-(-)	-(-)	-(-)	-(-)	1(1)	3(T)	7(1)	-(-)	-(-)	-(-)
ASTER OCCIDENTALIS	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	(-)	-(-)	-(-)	-(-)	-(-)
ASTRAGALUS MISER	-(-)	-(-)	4(1)	14(10)	41(6)	3(10)	40(8)	-(-)	35(3)	-(-)	63(8)
CAMPANULA ROTUNDIFOLIA	-(-)	-(-)	-(-)	-(-)	6(T)	-(-)	1(2)	-(-)	5(T)	-(-)	-(-)
CASTILLEJA MINIATA	75(T)	15(T)	13(1)	7(T)	26(T)	12(1)	16(1)	-(-)	15(T)	-(-)	-(-)
CHENOPODIUM FREMONTII	-(-)	8(T)	6(T)	-(-)	-(-)	13(1)	3(1)	7(T)	-(-)	10(T)	-(-)
CHLOROCRAMBE HASTATA	-(-)	-(-)	2(T)	-(-)	-(-)	1(T)	-(-)	-(-)	-(-)	-(-)	-(-)
CIRCAEA ALPINA	-(-)	-(-)	2(2)	-(-)	-(-)	1(5)	-(-)	-(-)	-(-)	-(-)	-(-)
CIRSIUM ARVENSE	-(-)	-(-)	-(-)	14(T)	15(2)	5(T)	5(4)	7(T)	15(T)	-(-)	-(-)
CIRSIUM VULGARE	-(-)	-(-)	-(-)	7(T)	-(-)	-(-)	1(T)	-(-)	-( )	-(-)	-(-)
CLEMATIS COLUMBIANA	-(-)	8(8)	2(7)	-(-)	-(-)	3(1)	1(T)	-(-)	-(-)	30(1)	-(-)
COLLINSIA PARVIFLORA	-(-)	8(T)	6(1)	7(T)	3(3)	19(6)	5(3)	4(T)	-(-)	20(2)	-(-)
COLLOMIA LINEARIS	-(-)	-(-)	6(T)	-(-)	-(-)	23(2)	3(T)	19(1)	5(T)	10(2)	-(-)
CORALLORHIZA MACULATA	-(-)	-(-)	4(T)	-(-)	12(T)	5(T)	6(T)	-(-)	-(-)	20(T)	-(-)
DELPHINIUM NUTTALLIANUM	-(-)	8(T)	8(T)	14(T)	3(T)	10(T)	5(T)	-(-)	-(-)	20(T)	-(-)
DELPHINIUM OCCIDENTALE	-(-)	-(-)	21(6)	-(-)	-(-)	23(4)	1(T)	15(4)	-(-)	10(T)	-(-)
DESCURAINIA CALIFORNICA	-(-)	-(-)	-(-)	-(-)	-(-)	4(2)	1(T)	-(-)	-( )	-(-)	-(-)
DESCURAINIA RICHARDSONII	-(-)	15(T)	27(1)	14(1)	6(T)	35(1)	8(1)	22(T)	5(T)	10(T)	13(T)
EPILOBIUM ANGUSTIFOLIUM	25(T)	23(T)	4(T)	-(-)	9(T)	7(T)	14(T)	-(-)	-(-)	-(-)	-(-)
ERIGERON FLAGELLARIS	-(-)	-(-)	-(-)	7(T)	9(T)	-(-)	6(T)	-(-)	5(T)	-(-)	-(-)
ERIGERON PEREGRINUS	-(-)	-(-)	-(-)	-(-)	6(1)	1(2)	3(3)	-(-)	-(-)	-(-)	13(10)
ERIGERON SPECIOSUS	25(T)	8(5)	27(1)	29(2)	12(1)	18(2)	4(T)	11(T)	5(T)	20(T)	13(3)
ERIGERON URSINUS	-(-)	-(-)	-(-)	-(-)	6(T)	1(5)	1(T)	-(-)	5(T)	-(-)	-(-)
ERYTHRONIUM GRANDIFLORUM	25(5)	-(-)	4(T)	7(T)	-(-)	4(2)	-(-)	-(-)	-(-)	10(T)	-(-)
FRAGARIA VESCA	25(T)	38(3)	27(2)	29(1)	44(3)	29(1)	44(1)	15(3)	25(3)	40(1)	50(1)
FRASERA SPECIOSA	-(-)	46(1)	19(T)	21(2)	18(1)	11(1)	6(1)	41(1)	5(T)	-(-)	25(2)
GALIUM APARINE	-(-)	-(-)	4(19)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	10(T)	-(-)
GALIUM BIFOLIUM	-(-)	15(T)	10(1)	14(2)	3(1)	20(8)	5(T)	11(5)	-(-)	20(1)	-(-)
GALIUM BOREALE	25(T)	38(1)	10(T)	7(2)	9(1)	11(T)	1(T)	30(1)	5(5)	30(1)	25(1)
GERANIUM RICHARDSONII	50(3)	8(2)	10(18)	7(10)	12(2)	14(7)	3(1)	19(1)	5(3)	-(-)	13(T)
GERANIUM VISCOSISSIMUM	-(-)	54(2)	38(3)	29(3)	29(1)	27(7)	8(5)	26(3)	5(T)	50(5)	13(T)
HABENARIA UNALASCENSIS	25(T)	-(-)	2(T)	-(-)	6(T)	3(T)	3(T)	-(-)	-(-)	10(T)	-(-)
HACKELIA FLORIBUNDA	-(-)	31(2)	44(3)	7(T)	6(T)	41(1)	-(-)	19(2)	-(-)	30(1)	-(-)
HAPLOPAPPUS PARRYI	-(-)	-(-)	2(T)	-(-)	-(-)	3(T)	10(3)	-(-)	5(5)	-(-)	13(7)
HELENIUM HOOPESII	-(-)	-(-)	4(1)	43(T)	6(T)	6(1)	6(4)	4(T)	15(T)	-(-)	-(-)
HELIANTHELLA UNIFLORA	-(-)	-(-)	4(3)	-(-)	-(-)	2(T)	5(T)	-(-)	-(-)	-(-)	13(T)
HERACLEUM LANATUM	-(-)	8(T)	8(3)	-(-)	-(-)	4(7)	-(-)	4(20)	-(-)	-(-)	-(-)
HIERACIUM ALBIFLORUM	-(-)	23(1)	2(T)	7(T)	-(-)	7(1)	3(T)	-(-)	-(-)	-(-)	-(-)
HYDROPHYLLUM CAPITATUM	25(T)	15(T)	17(T)	7(T)	-(-)	16(1)	4(T)	-(-)	-(-)	30(1)	-(-)
HYDROPHYLLUM FENDLERI	-(-)	-(-)	-(-)	-(-)	-(-)	2(5)	-(-)	-(-)	-(-)	-(-)	-(-)
IRIS MISSOURIENSIS	-(-)	-(-)	-(-)	-(-)	3(2)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
LATHYRUS ARIZONICUS	-(-)	-(-)	-(-)	-(-)	3(T)	-(-)	1(65)	-(-)	-(-)	-(-)	-(-)
LATHYRUS LANSZWERTII	25(30)	23(13)	31(14)	43(21)	12(20)	40(18)	10(24)	37(20)	5(25)	20(12)	-(-)
LATHYRUS LEUCANTHUS	-(-)	23(24)	15(23)	36(18)	3(65)	23(24)	6(10)	4(10)	25(15)	40(42)	13(5)
LATHYRUS PAUCIFLORUS	-(-)	31(1)	8(4)	7(T)	-(-)	10(1)	-(-)	26(2)	-(-)	-(-)	-(-)
LIGUSTICUM FILICINUM	-(-)	-(-)	-(-)	-(-)	3(T)	4(T)	13(T)	4(T)	-(-)	-(-)	-(-)
LIGUSTICUM PORTERI	-(-)	15(13)	13(2)	43(2)	18(2)	7(4)	17(1)	15(T)	30(1)	10(13)	13(T)
LUPINUS ARGENTEUS	-(-)	23(4)	21(1)	29(13)	26(4)	18(9)	29(10)	15(1)	5(5)	10(T)	50(3)
LUPINUS CAUDATUS	-(-)	15(4)	4(1)	-(-)	-(-)	1(1)	-(-)	-(-)	-(-)	10(T)	-(-)

APPENDIX A. (Con.)

	POTR-ABLA/VACA C.T.	POTR-ABLA/AMAL C.T.	POTR-ABLA/SYOR/SESE C.T.	POTR-ABLA/SYOR/CAGE C.T.	POTR-ABLA/JUCO C.T.	POTR-ABLA/SESE C.T.	POTR-ABLA/CAGE C.T.	POTR-ABCO/SYOR C.T.	POTR-ABCO/JUCO C.T.	POTR-PSME/AMAL C.T.	POTR-PSME/JUCO C.T.
Number of Stands:	4	13	48	14	34	94	77	27	20	10	8
FORBS (CONT'D)											
MERTENSIA ARIZONICA	(-)	8(5)	40(4)	-(-)	6(2)	31(7)	6(T)	22(6)	5(T)	-(-)	-(-)
MERTENSIA CILIATA	-(-)	-(-)	-(-)	-(-)	-(-)	1(2)	-(-)	-(-)	-(-)	-(-)	-(-)
MERTENSIA FRANCISCANA	-(-)	8(3)	8(13)	7(T)	-(-)	2(5)	-(-)	-(-)	-(-)	-(-)	-(-)
MERTENSIA LONGIFLORA	-(-)	-(-)	-(-)	(-)	-(-)	2(21)	-(-)	-(-)	-(-)	10(T)	-(-)
NEMOPHILA BREVIFLORA	-(-)	8(20)	21(16)	-(-)	-(-)	17(16)	-(-)	11(13)	-(-)	40(2)	-(-)
OSMORHIZA CHILENSIS	75(T)	46(1)	48(2)	43(1)	21(1)	63(2)	18(2)	81(3)	25(T)	70(5)	-(-)
OSMORHIZA OCCIDENTALIS	( )	15(T)	17(2)	14(T)	-(-)	23(1)	-(-)	19(1)	5(T)	20(8)	-(-)
PEDICULARIS RACEMOSA	-(-)	8(5)	-(-)	-(-)	-(-)	2(1)	4(10)	-(-)	-(-)	-(-)	-(-)
PENSTEMON PROCERUS	-(-)	-(-)	2(T)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
PENSTEMON RYDBERGII	(-)	-(-)	-(-)	-(-)	-(-)	4(1)	1(T)	-(-)	-(-)	10(5)	-(-)
PHACELIA HETEROPHYLLA	25(T)	8(T)	17(1)	-(-)	-(-)	11(1)	1(T)	7(T)	5(T)	20(T)	-(-)
POLEMONIUM FOLIOSISSIMUM	-(-)	8(T)	23(2)	7(T)	-(-)	24(1)	-(-)	15(T)	-(-)	-(-)	-(-)
POLYGONUM DOUGLASII	-(-)	8(T)	10(1)	14(T)	3(T)	23(4)	9(T)	11(3)	-(-)	10(10)	-(-)
POTENTILLA DIVERSIFOLIA	-(-)	-(-)	-(-)	-(-)	15(1)	-(-)	8(T)	-(-)	10(T)	-(-)	13(T)
POTENTILLA GLANDULOSA	-(-)	8(T)	13(1)	14(T)	9(T)	21(1)	6(T)	-(-)	-(-)	10(T)	-(-)
POTENTILLA GRACILIS	(-)	-(-)	4(3)	14(T)	15(T)	11(T)	17(1)	-(-)	-(-)	-(-)	13(T)
PTERIDIUM AQUILINUM	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
RANUNCULUS INAMOENUS	-(-)	-(-)	2(T)	-(-)	9(T)	9(T)	8(T)	-(-)	-(-)	-(-)	-(-)
RUDBECKIA OCCIDENTALIS	-( )	31(1)	52(10)	7(T)	-(-)	55(8)	-(-)	41(4)	-(-)	50(T)	-(-)
SCROPHULARIA LANCEOLATA	-(-)	-(-)	15(2)	-(-)	-(-)	7(1)	-(-)	11(T)	-(-)	-(-)	-(-)
SENECIO CYMBALARIOIDES	-(-)	-(-)	17(1)	-(-)	3(T)	13(1)	1(T)	11(T)	-(-)	20(T)	-(-)
SENECIO INTEGERRIMUS	-(-)	-(-)	2(T)	-(-)	3(T)	3(T)	4(1)	-(-)	-(-)	-(-)	-(-)
SENECIO SERRA	-(-)	46(4)	46(4)	-(-)	3(2)	27(3)	-(-)	19(4)	-(-)	20(T)	-(-)
SENECIO VULGARIS	-(-)	-(-)	-(-)	-(-)	9(T)	-(-)	6(1)	-(-)	5(T)	-(-)	13(3)
SIDALCEA OREGANA	-(-)	-(-)	2(3)	7(T)	-(-)	-(-)	-(-)	4(T)	-(-)	-(-)	-(-)
SILENE MENZIESII	-(-)	23(T)	10(T)	-(-)	3(T)	17(1)	4(1)	-(-)	-(-)	70(T)	-(-)
SMILACINA RACEMOSA	-(-)	15(T)	4(T)	-(-)	-(-)	10(T)	-(-)	4(T)	-(-)	60(1)	-(-)
SMILACINA STELLATA	-(-)	15(T)	23(1)	29(1)	3(T)	13(1)	8(T)	11(1)	-(-)	30(5)	25(T)
STELLARIA JAMESIANA	-(-)	46(2)	38(2)	21(2)	3(1)	56(2)	14(1)	63(1)	5(T)	40(T)	-(-)
TARAXACUM OFFICINALE	-(-)	23(T)	38(1)	64(4)	65(5)	50(2)	61(1)	48(2)	65(6)	40(T)	50(5)
THALICTRUM FENDLERI	(-)	85(9)	75(10)	79(7)	41(4)	66(6)	35(4)	30(3)	35(3)	60(5)	38(3)
THERMOPSIS MONTANA	-(-)	-(-)	2(2)	14(8)	-(-)	-(-)	1(13)	-(-)	-(-)	-(-)	-(-)
TRAGOPOGON DUBIUS	(-)	-(-)	2(T)	-(-)	3(T)	3(T)	3(T)	-(-)	5(T)	10(T)	-(-)
TRIFOLIUM LONGIPES	-(-)	-(-)	2(5)	-(-)	15(3)	4(13)	21(15)	4(T)	5(5)	-(-)	-(-)
URTICA DIOICA	-(-)	-(-)	-(-)	-(-)	-(-)	1(3)	-(-)	-(-)	-(-)	-(-)	-(-)
VALERIANA OCCIDENTALIS	-(-)	31(2)	40(7)	14(T)	-(-)	34(4)	-(-)	33(3)	-(-)	10(5)	-(-)
VERATRUM CALIFORNICUM	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)	-(-)
VICIA AMERICANA	-(-)	15(5)	42(6)	29(6)	15(8)	24(6)	10(10)	37(6)	20(14)	20(1)	-(-)
VIGUIERA MULTIFLORA	-(-)	-(-)	8(1)	-(-)	3(T)	3(2)	-(-)	7(T)	-(-)	-(-)	-(-)
VIOLA ADUNCA	(-)	46(1)	15(T)	-(-)	12(T)	17(1)	5(2)	26(2)	-(-)	30(1)	-(-)
VIOLA CANADENSIS	-(-)	8(T)	6(3)	14(T)	6(5)	6(2)	6(1)	-(-)	-(-)	-(-)	-(-)
VIOLA NUTTALLII	(-)	-(-)	8(T)	7(T)	-(-)	27(1)	4(1)	7(1)	-(-)	20(T)	-(-)

APPENDIX A. (Con.)

	POTR-PIPO/QUGA C.T.	POTR-PIPO/JUCO C.T.	POTR-PICO/VASC C.T.	POTR-PICO/JUCO C.T.
Number of Stands:	6	14	6	29
TREES				
ABIES CONCOLOR	-(-)	14(1)	-(-)	-(-)
ABIES LASIOCARPA	-(-)	-(-)	67(2)	28(2)
PICEA ENGELMANNII	-(-)	-(-)	17(T)	3(2)
PICEA PUNGENS	-(-)	21(1)	17(3)	21(1)
PINUS CONTORTA	-(-)	7(17)	100(32)	100(23)
PINUS FLEXILIS	-(-)	7(T)	-(-)	-(-)
PINUS PONDEROSA	100(14)	100(29)	-(-)	-(-)
POPULUS TREMULOIDES	100(63)	100(56)	100(41)	100(62)
PSEUDOTSUGA MENZIESII	-(-)	29(2)	-(-)	7(3)
SHRUBS				
ACER GLABRUM	-(-)	-( )	-(-)	-(-)
ACER GRANDIDENTATUM	-(-)	-(-)	-(-)	-(-)
AMELANCHIER ALNIFOLIA	50(13)	29(T)	50(1)	21(1)
ARCTOSTAPHYLOS UVA-URSI	17(5)	21(11)	17(1)	28(7)
ARTEMISIA TRIDENTATA	-(-)	21(3)	-(-)	7(8)
BERBERIS REPENS	50(1)	64(2)	83(1)	62(5)
CEANOTHUS VELUTINUS	-(-)	-(-)	17(10)	-(-)
CHRYSOTHAMNUS VISCIDIFLORUS	-(-)	-(-)	-(-)	-(-)
JUNIPERUS COMMUNIS	-(-)	93(5)	67(1)	100(10)
PACHISTIMA MYRSINITES	-(-)	7(T)	83(1)	21(T)
PHYSOCARPUS MALVACEUS	-(-)	-(-)	-(-)	-(-)
PRUNUS VIRGINIANA	33(3)	-(-)	-(-)	-(-)
QUERCUS GAMBELII	83(22)	-(-)	-(-)	-(-)
RIBES LACUSTRE	-(-)	-(-)	17(2)	-(-)
RIBES MONTIGENUM	-(-)	-(-)	-(-)	-(-)
RIBES SP.	-(-)	14(3)	-(-)	-(-)
ROSA WOODSII	50(3)	36(T)	50(1)	48(2)
RUBUS PARVIFLORUS	17(T)	-(-)	33(1)	-(-)
SALIX SCOULERIANA	17(T)	-(-)	33(1)	-(-)
SAMBUCUS RACEMOSA	-(-)	-(-)	-(-)	-(-)
SHEPHERDIA CANADENSIS	-(-)	-(-)	-(-)	10(T)
SORBUS SCOPULINA	-(-)	-(-)	-(-)	-(-)
SYMPHORICARPOS OREOPHILUS	83(37)	50(6)	17(T)	28(8)
VACCINIUM CAESPITOSUM	-(-)	-(-)	33(2)	-(-)
VACCINIUM SCOPARIUM	-(-)	-(-)	83(13)	-(-)
GRAMINOIDS				
AGROPYRON TRACHYCAULUM	17(T)	29(2)	-(-)	62(3)
ARRHENATHERUM ELATIUS	-(-)	-(-)	-(-)	-(-)
BROMUS ANOMALUS	-(-)	21(5)	-(-)	-(-)
BROMUS CARINATUS	33(2)	7(T)	17(T)	7(T)
BROMUS CILIATUS	-(-)	7(1)	17(T)	45(2)
CALAMAGROSTIS RUBESCENS	-(-)	-(-)	17(70)	-(-)
CAREX GEYERI	33(59)	-(-)	83(11)	76(13)
CAREX HOODII	-(-)	-(-)	-(-)	-(-)
CAREX OBTUSATA	-(-)	-(-)	-(-)	-(-)
CAREX ROSSII	17(1)	50(1)	-(-)	7(1)
DACTYLIS GLOMERATA	17(10)	-(-)	-(-)	-(-)
ELYMUS CINEREUS	-(-)	-(-)	-(-)	-(-)
ELYMUS GLAUCUS	17(2)	-(-)	50(14)	-(-)
FESTUCA IDAHOENSIS	-(-)	-(-)	-(-)	14(6)
FESTUCA THURBERI	17(T)	-(-)	-(-)	-(-)
KOELERIA CRISTATA	17(3)	7(T)	17(T)	-(-)
LEUCOPOA KINGII	-(-)	-(-)	-(-)	-(-)
MELICA SPECTABILIS	-(-)	-(-)	-(-)	3(T)
PHLEUM ALPINUM	-(-)	-(-)	33(1)	-(-)
POA FENDLERIANA	17(3)	57(3)	-(-)	7(6)
POA NERVOSA	-(-)	7(2)	17(T)	10(1)
POA PRATENSIS	83(16)	21(2)	-(-)	31(5)
SITANION HYSTRIX	17(1)	57(5)	-(-)	-(-)
STIPA COMATA	-(-)	29(10)	-(-)	-(-)
STIPA LETTERMANII	-(-)	7(1)	-(-)	3(T)
STIPA OCCIDENTALIS	17(T)	21(T)	-(-)	76(5)
TRISETUM SPICATUM	17(T)	-(-)	50(2)	38(1)

APPENDIX A. (Con.)

	POTR-PIPO/QUGA C.T.	POTR-PIPO/JUCO C.T.	POTR-PICO/VASC C.T.	POTR-PICO/JUCO C.T.
Number of Stands:	6	14	6	29
FORBS				
ACHILLEA MILLEFOLIUM	83(T)	36(2)	50(1)	90(2)
ACTAEA RUBRA	-(-)	-(-)	17(1)	-(-)
AGASTACHE URTICIFOLIA	-(-)	-(-)	-(-)	3(3)
AGOSERIS GLAUCA	-(-)	14(T)	-(-)	21(T)
ALLIUM BREVISTYLUM	(-)	7(T)	-(-)	7(7)
ALLIUM CERNUUM	-(-)	7(T)	(-)	3(T)
ANTENNARIA MICROPHYLLA	-(-)	43(T)	33(5)	55(1)
ANTENNARIA PARVIFOLIA	-(-)	-(-)	-(-)	-(-)
APOCYNUM ANDROSAEMIFOLIUM	-(-)	-(-)	-(-)	3(T)
AQUILEGIA COERULEA	-(-)	-(-)	17(1)	14(1)
ARENARIA CONGESTA	-(-)	7(T)	-(-)	7(1)
ARNICA CORDIFOLIA	-( )	-(-)	33(1)	7(1)
ARNICA LATIFOLIA	-(-)	-(-)	33(15)	38(8)
ARTEMISIA LUDOVICIANA	-(-)	-(-)	-(-)	-(-)
ASTER CHILENSIS	-(-)	-(-)	-(-)	-(-)
ASTER ENGELMANNII	-(-)	-(-)	17(T)	3(T)
ASTER FOLIACEUS	-(-)	-(-)	-(-)	-(-)
ASTER OCCIDENTALIS	-(-)	-(-)	-(-)	10(17)
ASTRAGALUS MISER	-(-)	29(4)	-(-)	66(15)
CAMPANULA ROTUNDIFOLIA	-(-)	-(-)	33(T)	10(1)
CASTILLEJA MINIATA	-(-)	-(-)	33(1)	31(1)
CHENOPODIUM FREMONTII	-(-)	-(-)	-(-)	3(T)
CHLOROCRAMBE HASTATA	-(-)	-(-)	-(-)	-(-)
CIRCAEA ALPINA	-(-)	-(-)	-(-)	-(-)
CIRSIUM ARVENSE	-(-)	-(-)	-(-)	-(-)
CIRSIUM VULGARE	-(-)	-(-)	-(-)	-(-)
CLEMATIS COLUMBIANA	-(-)	-(-)	17(1)	3(T)
COLLINSIA PARVIFLORA	17(T)	-(-)	-(-)	7(1)
COLLOMIA LINEARIS	-(-)	-(-)	-(-)	-(-)
CORALLORHIZA MACULATA	17(T)	-(-)	-(-)	3(T)
DELPHINIUM NUTTALLIANUM	17(T)	-(-)	-(-)	7(2)
DELPHINIUM OCCIDENTALE	-(-)	-(-)	-(-)	-(-)
DESCURAINIA CALIFORNICA	-(-)	-(-)	-(-)	-(-)
DESCURAINIA RICHARDSONII	-(-)	7(T)	-(-)	3(T)
EPILOBIUM ANGUSTIFOLIUM	17(T)	-(-)	-(-)	14(T)
ERIGERON FLAGELLARIS	-(-)	-(-)	-(-)	3(T)
ERIGERON PEREGRINUS	-(-)	-(-)	(-)	34(5)
ERIGERON SPECIOSUS	17(T)	21(1)	-(-)	14(T)
ERIGERON URSINUS	17(T)	7(2)	-(-)	3(T)
ERYTHRONIUM GRANDIFLORUM	-(-)	-(-)	-(-)	-(-)
FRAGARIA VESCA	17(10)	43(1)	33(1)	48(2)
FRASERA SPECIOSA	17(T)	-(-)	-(-)	24(2)
GALIUM APARINE	-(-)	-(-)	-(-)	3(T)
GALIUM BIFOLIUM	-(-)	-(-)	-(-)	3(T)
GALIUM BOREALE	-(-)	7(T)	50(1)	45(T)
GERANIUM RICHARDSONII	-(-)	-(-)	17(10)	14(2)
GERANIUM VISCOSISSIMUM	33(T)	29(1)	17(10)	62(2)
HABENARIA UNALASCENSIS	-(-)	-(-)	17(T)	-(-)
HACKELIA FLORIBUNDA	-(-)	-(-)	-(-)	7(T)
HAPLOPAPPUS PARRYI	-(-)	-( )	-(-)	10(6)
HELENIUM HOOPESII	-(-)	-(-)	17(T)	-(-)
HELIANTHELLA UNIFLORA	-(-)	-(-)	-(-)	3(T)
HERACLEUM LANATUM	-(-)	-(-)	-(-)	-(-)
HIERACIUM ALBIFLORUM	-(-)	-(-)	17(T)	14(T)
HYDROPHYLLUM CAPITATUM	-(-)	-(-)	-(-)	-(-)
HYDROPHYLLUM FENDLERI	-(-)	-(-)	-(-)	-(-)
IRIS MISSOURIENSIS	-(-)	-(-)	-(-)	-(-)
LATHYRUS ARIZONICUS	-(-)	(-)	-(-)	-(-)
LATHYRUS LANSZWERTII	17(5)	-(-)	50(5)	21(12)
LATHYRUS LEUCANTHUS	33(24)	7(T)	-(-)	-(-)
LATHYRUS PAUCIFLORUS	-(-)	-(-)	-(-)	-(-)
LIGUSTICUM FILICINUM	-(-)	-(-)	17(T)	7(2)
LIGUSTICUM PORTERI	50(3)	-(-)	-(-)	3(3)
LUPINUS ARGENTEUS	17(1)	29(4)	17(3)	66(6)
LUPINUS CAUDATUS	-(-)	-(-)	-(-)	-(-)

APPENDIX A. (Con.)

	POTR-PIPO/QUGA C.T.	POTR-PIPO/JUCO C.T.	POTR-PICO/VASC C.T.	POTR-PICO/JUCO C.T.
Number of Stands:	6	14	6	29
FORBS (CONT'D)				
MERTENSIA ARIZONICA	-(-)	-(-)	-(-)	-(-)
MERTENSIA CILIATA	-(-)	-(-)	17(T)	-(-)
MERTENSIA FRANCISCANA	-(-)	-(-)	(-)	-(-)
MERTENSIA LONGIFLORA	-(-)	-(-)	-(-)	-(-)
NEMOPHILA BREVIFLORA	-(-)	-(-)	-(-)	-(-)
OSMORHIZA CHILENSIS	17(5)	7(T)	50(3)	38(1)
OSMORHIZA OCCIDENTALIS	-(-)	-(-)	-(-)	-(-)
PEDICULARIS RACEMOSA	-(-)	-(-)	-(-)	-(-)
PENSTEMON PROCERUS	-(-)	-(-)	-(-)	-(-)
PENSTEMON RYDBERGII	-(-)	-(-)	-(-)	-(-)
PHACELIA HETEROPHYLLA	-(-)	-(-)	-(-)	-(-)
POLEMONIUM FOLIOSISSIMUM	-(-)	-(-)	-(-)	-(-)
POLYGONUM DOUGLASII	-(-)	-(-)	-(-)	3(T)
POTENTILLA DIVERSIFOLIA	17(T)	7(T)	-(-)	3(T)
POTENTILLA GLANDULOSA	-(-)	-(-)	-(-)	-(-)
POTENTILLA GRACILIS	17(T)	-(-)	17(T)	41(1)
PTERIDIUM AQUILINUM	-(-)	-(-)	-(-)	-(-)
RANUNCULUS INAMOENUS	-(-)	-(-)	-(-)	-(-)
RUDBECKIA OCCIDENTALIS	-(-)	-(-)	-(-)	-(-)
SCROPHULARIA LANCEOLATA	-(-)	-(-)	-(-)	-(-)
SENECIO CYMBALARIOIDES	17(T)	-(-)	-(-)	3(T)
SENECIO INTEGERRIMUS	-(-)	-(-)	-(-)	-(-)
SENECIO SERRA	-(-)	-(-)	-(-)	-(-)
SENECIO VULGARIS	-(-)	29(1)	-(-)	-(-)
SIDALCEA OREGANA	-(-)	-(-)	-(-)	-(-)
SILENE MENZIESII	-(-)	-(-)	-(-)	7(T)
SMILACINA RACEMOSA	-(-)	-(-)	-(-)	-(-)
SMILACINA STELLATA	33(2)	-(-)	33(T)	14(1)
STELLARIA JAMESIANA	33(T)	7(T)	17(T)	14(1)
TARAXACUM OFFICINALE	50(4)	57(1)	17(1)	59(4)
THALICTRUM FENDLERI	67(7)	21(T)	33(2)	55(10)
THERMOPSIS MONTANA	67(9)	-(-)	-(-)	7(4)
TRAGOPOGON DUBIUS	-(-)	-(-)	-(-)	-(-)
TRIFOLIUM LONGIPES	-(-)	7(3)	17(T)	21(9)
URTICA DIOICA	-(-)	-(-)	-(-)	-(-)
VALERIANA OCCIDENTALIS	-(-)	-(-)	-(-)	-(-)
VERATRUM CALIFORNICUM	-(-)	-(-)	17(4)	-(-)
VICIA AMERICANA	-(-)	7(T)	-(-)	3(T)
VIGUIERA MULTIFLORA	-(-)	-(-)	-(-)	-(-)
VIOLA ADUNCA	-(-)	-(-)	17(T)	14(T)
VIOLA CANADENSIS	-(-)	-(-)	17(2)	-(-)
VIOLA NUTTALLII	-(-)	-(-)	-(-)	3(T)

APPENDIX B1: MEANS, STANDARD ERROR (SE), AND RANGES OF BASAL AREA, STAND AGE, STAND HEIGHT, AND SITE INDEX FOR *POPULUS TREMULOIDES* BY COMMUNITY TYPES IN UTAH, IN METRIC UNITS

Community type	*P. tremuloides* basal area	Stand age	Stand height	Site index at 80 years
	m^2/ha	*Years*	*Meters*	
POTR/ACGR/PTAQ (5)[1]				
mean	31.2	73	16.8	18.0
SE	2.4	13	0.8	1.4
range	25.8-40.0	58-119	16.2-18.9	13.7-21.0
POTR/PRVI/SESE (42)				
mean	27.9	78	14.2	14.4
SE	1.3	3	0.5	0.5
range	10.4-46.4	51-126	8.8-22.6	9.4-20.7
POTR/PRVI/CAGE (7)				
mean	23.4	82	14.2	14.1
SE	2.7	8	1.4	1.2
range	16.3-35.7	59-112	10.1-21.0	10.4-18.9
POTR/SARA (8)				
mean	34.3	89	17.0	16.5
SE	4.3	12	1.1	1.0
range	16.1-48.5	52-144	12.8-22.0	11.6-19.8
POTR/SYOR/SESE (42)				
mean	26.0	88	15.1	14.5
SE	1.8	4	0.6	0.5
range	3.3-53.4	48-142	6.7-22.6	7.9-21.6
POTR/SYOR/CAGE (14)				
mean	37.4	87	16.5	15.3
SE	4.0	7	1.5	1.1
range	16.9-67.0	42-141	8.5-21.6	10.7-22.9
POTR/SYOR/FETH (2)				
mean	38.7	84	18.0	17.5
SE	1.9	10	0.6	1.7
range	36.8-40.6	75-94	17.4-18.6	15.8-19.2
POTR/JUCO/CAGE (11)				
mean	32.9	99	15.5	13.7
SE	3.9	4	1.2	1.0
range	10.5-51.7	78-122	8.8-23.2	7.0-20.7
POTR/SYOR/BRCA (2)				
mean	22.3	72	16.0	16.8
SE	0.1	1	2.3	2.1
range	22.2-22.3	71-73	13.7-18.3	14.6-18.9
POTR/SYOR/POPR (3)				
mean	26.9	77	13.9	14.2
SE	4.9	7	1.1	0.6
range	22.0-36.7	67-91	11.9-15.5	13.1-15.2
POTR/VECA (1)				
mean	16.4	41	14.6	21.3
SE	—	—	—	—
range	—	—	—	—
POTR/HELA (5)				
mean	42.0	86	20.7	19.9
SE	8.5	7	2.4	1.9
range	20.0-65.1	59-93	14.9-25.9	13.7-23.8
POTR/PTAQ (5)				
mean	33.4	93	19.8	18.3
SE	5.6	4	1.8	1.7
range	16.6-51.4	82-105	15.2-25.9	14.3-23.8
POTR/SESE (64)				
mean	34.7	93	17.5	16.5
SE	1.6	3	0.5	0.4
range	10.7-69.4	43-163	10.1-27.1	9.8-25.9

(con.)

APPENDIX B1. (Con.)

Community type	*P. tremuloides* basal area	Stand age	Stand height	Site index at 80 years
	m^2/ha	Years	Meters	
POTR/CAGE (24)				
mean	38.9	91	16.7	15.7
SE	3.2	4	0.9	0.8
range	20.5-73.9	42-125	8.5-25.6	9.8-23.5
POTR/FETH (5)				
mean	45.5	104	20.3	17 9
SE	7.6	11	1.5	0.6
range	30.7-74.2	73-136	15.2-24.4	16.2-19.2
POTR/SIHY (5)				
mean	34.3	96	14.9	14.3
SE	4.7	11	1.8	1.7
range	21.3-45.5	73-137	11.9-22.0	9.1-19.2
POTR/BRCA (7)				
mean	29.5	90	18.0	17.0
SE	4.5	8	1.2	1.2
range	9.0-43.4	64-119	13.4-24.1	14.6-24.1
POTR/POPR (9)				
mean	28.6	98	17.8	16.1
SE	3.1	9	1.7	1.5
range	16.3-44.3	63-136	8.2-24.1	9.1-21.3
POTR-ABLA/AMAL (6)				
mean	29.4	97	17.7	16.5
SE	6.8	9	1.6	0.8
range	9.9-58.6	61-127	14.0-23.2	14.3-20.1
POTR-ABLA/SYOR/SESE (14)				
mean	33.0	96	18.1	16.6
SE	2.5	3	0.9	1.0
range	14.8-48.9	79-129	13.1-23.2	10.1-22.6
POTR-ABLA/SYOR/CAGE (3)				
mean	20.7	100	13.1	11.5
SE	6.3	5	1.3	1.3
range	9.0-30.6	92-108	11.3-15.5	9.1-13.7
POTR-ABLA/JUCO (12)				
mean	34.4	100	17.5	15.7
SE	3.2	5	1.2	1.1
range	21.2-58.7	75-135	12.8-24.7	9.8-21.6
POTR-ABLA/SESE (49)				
mean	31.4	101	17.7	15.8
SE	1.7	3	0.5	0.4
range	15.8-78.5	66-151	9.4-25.0	10.1-22.6
POTR-ABLA/CAGE (36)				
mean	36.6	109	17.2	14.8
SE	2.2	5	0.6	0.5
range	10.8-65.0	62-117	8.5-26.2	7.6-19.5
POTR-ABCO/SYOR (8)				
mean	28.4	98	14.2	12.8
SE	2.2	6	1.1	1.2
range	20.9-36.9	68-112	10.7-19.2	8.8-19.2
POTR-PSME/AMAL (4)				
mean	31.4	100	20.3	18.3
SE	10.5	6	0.8	1.1
range	19.6-62.9	90-112	18.3-21.6	15.2-20.1
POTR-PIPO/QUGA (1)				
mean	29.1	118	14.9	12.2
SE	—	—	—	—
range	—	—	—	—

(con.)

APPENDIX B1. (Con.)

Community type	*P. tremuloides* basal area	Stand age	Stand height	Site index at 80 years
	m^2/ha	*Years*	*Meters*	
POTR-PIPO/JUCO (1)				
mean	25.5	139	23.5	17.4
SE	—	—	—	—
range	—	—	—	—
POTR-PICO/JUCO (6)				
mean	26.0	109	15.2	12.9
SE	2.1	9	0.6	0.7
range	19.4-32.9	92-152	13.4-16.8	11.3-15.5

[1]Number of intensively sampled stands.

APPENDIX B2: MEANS, STANDARD ERRORS (SE), AND RANGES OF BASAL AREA, STAND SIZE, STAND HEIGHT, AND SITE INDEX FOR *POPULUS TREMULOIDES* BY COMMUNITY TYPES IN UTAH, IN ENGLISH UNITS

Community type	*P. tremuloides* basal area	Stand age	Stand height	Site index at 80 years
	Ft^2/acre	*Years*	*Feet*	
POTR/ACGR/PTAQ (5)[1]				
mean	136	73	55	59
SE	10	13	2	4
range	113-174	45-119	47-62	45-69
POTR/PRVI/SESE (42)				
mean	121	78	47	47
SE	6	3	2	2
range	45-202	51-126	29-74	31-68
POTR/PRVI/CAGE (7)				
mean	102	82	47	46
SE	12	8	4	4
range	71-155	59-112	33-69	34-62
POTR/SARA (8)				
mean	149	89	56	54
SE	19	12	4	3
range	70-211	52-144	42-72	38-65
POTR/SYOR/SESE (42)				
mean	113	88	50	48
SE	8	4	2	2
range	14-233	48-142	22-74	26-71
POTR/SYOR/CAGE (14)				
mean	163	87	54	50
SE	17	7	5	4
range	74-292	42-141	28-82	35-75
POTR/SYOR/FETH (2)				
mean	168	84	59	58
SE	8	10	2	6
range	160-177	75-94	57-61	52-63
POTR/JUCO/CAGE (11)				
mean	143	99	51	45
SE	17	4	4	3
range	46-225	78-122	29-76	23-68
POTR/SYOR/BRCA (2)				
mean	97	72	52	55
SE	1	1	8	7
range	96-97	71-73	45-60	48-62

(con.)

APPENDIX B2. (Con.)

Community type	*P. tremuloides* basal area	Stand age	Stand height	Site index at 80 years
	Ft²/acre	*Years*	*Feet*	
POTR/SYOR/POPR (3)				
mean	117	77	46	47
SE	21	7	4	2
range	96-160	67-91	39-51	43-50
POTR/VECA (1)				
mean	71	41	48	70
SE	—	—	—	—
range	—	—	—	—
POTR/HELA (5)				
mean	183	86	68	65
SE	37	7	8	6
range	87-283	59-93	49-85	45-78
POTR/PTAQ (5)				
mean	145	93	65	60
SE	24	4	6	6
range	72-224	82-105	50-85	47-78
POTR/SESE (64)				
mean	151	93	58	54
SE	7	3	2	1
range	46-302	43-163	33-89	32-85
POTR/CAGE (24)				
mean	169	91	55	52
SE	14	4	3	2
range	89-322	42-125	28-84	32-77
POTR/FETH (5)				
mean	198	104	67	59
SE	33	11	5	2
range	134-323	73-136	50-80	53-63
POTR/SIHY (5)				
mean	150	96	49	47
SE	21	11	6	6
range	93-198	73-137	39-72	30-63
POTR/BRCA (7)				
mean	128	90	59	56
SE	20	8	4	4
range	39-189	64-119	44-79	48-79
POTR/POPR (9)				
mean	125	98	58	53
SE	14	9	5	5
range	71-193	63-136	27-79	30-70
POTR-ABLA/AMAL (6)				
mean	128	97	58	54
SE	30	9	5	3
range	43-255	61-127	46-76	47-66
POTR-ABLA/SYOR/SESE (14)				
mean	144	96	60	54
SE	11	3	3	3
range	64-213	79-129	43-76	33-74
POTR-ABLA/SYOR/CAGE (3)				
mean	90	100	43	38
SE	27	5	4	4
range	39-133	92-108	37-51	30-45
POTR-ABLA/JUCO (12)				
mean	150	100	57	52
SE	14	5	4	4
range	92-255	75-135	42-81	32-71

(con.)

APPENDIX B2. (Con.)

Community type	*P. tremuloides* basal area	Stand age	Stand height	Site index at 80 years
	Ft²/acre	*Years*	*Feet*	
POTR-ABLA/SESE (49)				
mean	137	101	58	52
SE	7	3	2	1
range	69-342	66-151	31-82	33-74
POTR-ABLA/CAGE (36)				
mean	160	109	56	48
SE	10	5	2	2
range	47-283	62-177	28-72	25-64
POTR-ABCO/SYOR (8)				
mean	124	98	47	42
SE	10	6	4	4
range	91-161	68-112	35-63	29-63
POTR-PSME/AMAL (4)				
mean	137	100	66	60
SE	46	6	2	4
range	85-274	90-112	60-71	50-66
POTR-PIPO/QUGA (1)				
mean	127	118	49	40
SE	—	—	—	—
range	—	—	—	—
POTR-PIPO/JUCO (1)				
mean	111	139	77	57
SE	—	—	—	—
range	—	—	—	—
POTR-PICO/JUCO (6)				
mean	113	109	50	42
SE	9	9	2	2
range	84-143	92-152	44-53	37-51

[1]Number of intensively sampled stands.

APPENDIX C: MEANS, STANDARD ERRORS (SE), AND RANGES OF TREE BASAL AREA, AND PERCENT OF THIS BASAL AREA CONSISTING OF CONIFERS, BY COMMUNITY TYPE IN UTAH

Community type	N[1]	Total basal area		Percent conifers
		m^2/ha	Ft^2/acre	
POTR/ACGR/PTAQ	5			
mean		31.2	136	0
SE		2.4	11	
range		25.8-40.0	113-174	
POTR/PRVI/SESE	42			
mean		28.0	122	T[2]
SE		1.3	5	
range		10.4-46.4	42-202	
POTR/PRVI/CAGE	7			
mean		23.8	104	2
SE		2.8	12	
range		16.2-35.7	71-155	
POTR/SARA	8			
mean		34.5	150	1
SE		4.3	19	
range		16.1-48.5	70-211	
POTR/SYOR/SESE	42			
mean		26.4	115	2
SE		1.8	8	
range		3.3-53.4	14-233	
POTR/SYOR/CAGE	14			
mean		37.8	165	1
SE		4.0	17	
range		16.9-67.0	74-292	
POTR/SYOR/FETH	2			
mean		38.9	169	1
SE		2.0	9	
range		36.8-40.9	160-178	
POTR/JUCO/CAGE	11			
mean		33.5	146	2
SE		4.0	17	
range		10.9-53.6	47-234	
POTR/SYOR/BRCA	2			
mean		23.7	103	6
SE		1.4	6	
range		22.3-25.1	97-109	
POTR/SYOR/POPR	3			
mean		26.9	117	0
SE		4.9	21	
range		22.0-36.7	96-160	
POTR/VECA	1			
mean		16.4	71	0
SE		—	—	
range		—	—	
POTR/HELA	5			
mean		42.0	183	0
SE		8.5	37	
range		19.9-65.1	87-283	
POTR/PTAQ	5			
mean		33.6	146	1
SE		5.4	24	
range		17.3-51.4	76-224	
POTR/SESE	64			
mean		35.0	152	1
SE		1.6	7	
range		10.7-69.4	46-302	

(con.)

APPENDIX C. (Con.)

Community type	N[1]	Total basal area		Percent conifers
		m^2/ha	$Ft^2/acre$	
POTR/CAGE	24			
mean		39.2	171	1
SE		3.2	14	
range		20.5-73.9	89-322	
POTR/FETH	5			
mean		45.6	199	T
SE		7.7	33	
range		30.8-74.6	134-325	
POTR/SIHY	5			
mean		35.7	155	4
SE		4.7	21	
range		21.5-46.6	94-203	
POTR/BRCA	7			
mean		29.6	129	T
SE		4.5	20	
range		9.0-43.4	39-189	
POTR/POPR	9			
mean		28.9	126	1
SE		3.1	13	
range		16.3-44.3	71-193	
POTR-ABLA/AMAL	6			
mean		34.4	150	15
SE		7.6	33	
range		12.1-66.2	53-288	
POTR-ABLA/SYOR/SESE	14			
mean		38.0	165	13
SE		3.3	14	
range		17.0-57.3	74-249	
POTR-ABLA/SYOR/CAGE	3			
mean		25.0	109	17
SE		5.1	22	
range		15.5-33.0	67-144	
POTR-ABLA/JUCO	12			
mean		38.1	166	10
SE		3.3	14	
range		22.5-60.4	98-263	
POTR-ABLA/SESE	49			
mean		40.7	177	23
SE		1.9	8	
range		20.4-80.6	89-351	
POTR-ABLA/CAGE	36			
mean		45.6	199	20
SE		2.1	9	
range		21.3-73.4	93-320	
POTR-ABCO/SYOR	8			
mean		40.7	177	30
SE		3.1	14	
range		24.2-49.3	106-215	
POTR-PSME/AMAL	4			
mean		36.7	160	14
SE		9.5	41	
range		24.2-64.9	105-283	
POTR-PIPO/QUGA	1			
mean		39.1	170	26
SE		—	—	
range		—	—	

(con.)

APPENDIX C. (Con.)

Community type	N[1]	Total basal area		Percent conifers
		m^2/ha	$Ft^2/acre$	
POTR-PIPO/JUCO	1			
mean		44.3	193	42
SE		—	—	
range		—	—	
POTR-PICO/JUCO	6			
mean		31.0	135	16
SE		2.6	11	
range		23.8-40.8	104-178	

[1]Number of intensively sampled stands.
[2]T = less than 0.5 percent.

APPENDIX D1: MEANS, STANDARD ERRORS (SE), AND RANGES OF ANNUAL UNDERGROWTH PRODUCTION BY VEGETATION CLASSES EXPRESSED IN DRY WEIGHT KILOGRAMS PER HECTARE

Community type	N[1]	Shrubs	Forbs	Graminoids	Total
			kg/ha		
POTR/ACGR/PTAQ	5				
mean		146	2,012	162	2,320
SE		112	559	105	577
range		18-594	882-4,001	9-552	938-4,256
POTR/PRVI/SESE	41				
mean		386	610	285	1,281
SE		37	56	61	64
range		29-894	68-1,490	0-2,102	572-2,627
POTR/PRVI/CAGE	6				
mean		502	275	317	1,094
SE		69	122	99	209
range		183-631	25-722	68-722	684-2,062
POTR/SARA	8				
mean		417	630	157	1,204
SE		111	130	72	170
range		72-895	138-1,327	10-540	552-2,159
POTR/SYOR/SESE	39				
mean		307	823	375	1,504
SE		54	100	62	114
range		26-1,687	95-2,513	6-1,375	434-2,956
POTR/SYOR/CAGE	14				
mean		274	534	394	1,202
SE		46	95	99	154
range		45-609	128-1,452	38-1,454	372-2,234
POTR/SYOR/FETH	2				
mean		374	178	110	662
SE		26	169	64	207
range		348-400	9-348	46-174	455-869
POTR/JUCO/CAGE	9				
mean		163	221	276	670
SE		66	55	65	113
range		8-579	20-472	49-630	158-1,158
POTR/SYOR/BRCA	2				
mean		135	331	681	1,148
SE		46	202	474	629
range		89-182	130-533	208-1,155	519-1,777
POTR/SYOR/POPR	3				
mean		339	360	345	1,042
SE		124	79	94	285
range		96-503	215-487	167-487	479-1,391
POTR/VECA	1				
mean		18	604	1,154	1,775
SE		—	—	—	—
range		—	—	—	—
POTR/HELA	5				
mean		220	1,044	114	1,378
SE		197	100	59	158
range		11-1,006	782-1,329	12-279	1,073-1,899
POTR/PTAQ	3				
mean		38	1,598	125	1,762
SE		20	487	65	420
range		12-78	930-2,546	0-221	1,162-2,572
POTR/SESE	59				
mean		46	923	321	1,289
SE		12	68	40	74
range		0-540	92-2,401	6-1,077	263-3,202

(con.)

APPENDIX D1. (Con.)

Community type	N[1]	Shrubs	Forbs	Graminoids	Total
			kg/ha		
POTR/CAGE	23				
mean		27	303	415	746
SE		8	58	72	83
range		4-191	35-999	9-1,108	88-1,447
POTR/FETH	5				
mean		13	557	797	1,367
SE		7	188	529	647
range		0-39	99-980	72-2,900	502-3,919
POTR/SIHY	5				
mean		11	271	249	530
SE		5	116	70	105
range		4-29	8-545	29-370	358-923
POTR/BRCA	5				
mean		60	626	683	1,369
SE		45	175	220	285
range		0-238	117-1,089	63-1,348	417-2,106
POTR/POPR	8				
mean		46	512	318	876
SE		18	148	58	135
range		0-131	35-1,063	20-478	340-1,445
POTR-ABLA/AMAL	6				
mean		752	503	155	1,410
SE		320	119	59	252
range		142-1,843	184-924	13-355	649-2,229
POTR-ABLA/SYOR/SESE	13				
mean		262	665	200	1,127
SE		55	106	79	157
range		24-646	74-1,572	2-833	227-2,380
POTR-ABLA/SYOR/CAGE	3				
mean		230	507	135	872
SE		123	278	8	209
range		36-457	142-1,053	121-147	491-1,210
POTR-ABLA/JUCO	12				
mean		142	151	127	420
SE		83	41	51	100
range		8-1,022	4-462	2-550	88-1,278
POTR-ABLA/SESE	46				
mean		25	597	241	861
SE		5	68	49	82
range		0-172	40-2,440	2-1,660	78-2,568
POTR-ABLA/CAGE	31				
mean		6	188	110	304
SE		2	36	28	50
range		0-25	1-791	1-675	3-1,026
POTR-ABCO/SYOR	7				
mean		185	217	71	473
SE		38	78	49	121
range		77-309	17-581	2-349	211-1,162
POTR-PSME/AMAL	4				
mean		322	344	173	839
SE		126	57	100	109
range		18-613	214-446	6-452	630-1,115
POTR-PIPO/QUGA	1				
mean		238	278	278	794
SE		—	—	—	—
range		—	—	—	—

(con.)

APPENDIX D1. (Con.)

Community type	N[1]	Shrubs	Forbs	Graminoids	Total
			kg/ha		
POTR-PIPO/JUCO	1				
mean		96	72	312	480
SE		—	—	—	—
range		—	—	—	—
POTR-PICO/JUCO	5				
mean		52	478	146	677
SE		31	123	41	98
range		7-176	16-740	35-287	326-925

[1]Number of intensively sampled stands.

APPENDIX D2: MEANS, STANDARD ERRORS (SE), AND RANGES OF ANNUAL UNDERGROWTH PRODUCTION BY VEGETATION CLASSES EXPRESSED IN DRY WEIGHT POUNDS PER ACRE

Community type	N[1]	Shrubs	Forbs	Graminoids	Total
			Lb/acre		
POTR/ACGR/PTAQ	5				
mean		130	1,793	144	2,068
SE		100	498	93	514
range		16-529	786-3,565	8-492	836-3,792
POTR/PRVI/SESE	41				
mean		344	543	254	1,141
SE		33	50	55	57
range		25-797	61-1,328	0-1,873	509-2,341
POTR/PRVI/CAGE	6				
mean		447	245	282	975
SE		62	109	88	186
range		163-563	22-643	61-643	609-1,838
POTR/SARA	8				
mean		372	561	140	1,072
SE		99	116	64	152
range		64-797	123-1,182	9-481	491-1,924
POTR/SYOR/SESE	39				
mean		273	733	334	1,340
SE		48	89	55	102
range		23-1,503	85-2,239	6-1,226	386-2,634
POTR/SYOR/CAGE	14				
mean		244	476	351	1,071
SE		41	85	88	137
range		40-542	114-1,294	33-1,295	331-1,990
POTR/SYOR/FETH	2				
mean		333	159	98	590
SE		24	151	57	184
range		310-357	8-310	41-155	405-774
POTR/JUCO/CAGE	9				
mean		146	197	246	597
SE		59	49	58	101
range		7-516	18-421	44-561	141-1,031
POTR/SYOR/BRCA	2				
mean		121	295	607	1,023
SE		41	180	422	560
range		79-162	116-475	185-1,029	463-1,583

(con.)

APPENDIX D2. (Con.)

Community type	N[1]	Shrubs	Forbs	Graminoids	Total
			Lb/acre		
POTR/SYOR/POPR	3				
mean		302	321	306	929
SE		110	70	84	254
range		85-448	192-434	149-434	426-1,240
POTR/VECA	1				
mean		16	538	1,028	1,582
SE		—	—	—	—
range		—	—	—	—
POTR/HELA	5				
mean		196	930	101	1,228
SE		175	89	53	141
range		10-897	697-1,184	11-249	956-1,692
POTR/PTAQ	3				
mean		34	1,424	112	1,570
SE		18	434	58	375
range		10-69	828-2,269	0-197	1,035-2,292
POTR/SESE	59				
mean		41	822	286	1,149
SE		11	60	36	66
range		0-481	82-2,140	6-960	234-2,853
POTR/CAGE	23				
mean		24	270	370	665
SE		7	52	64	74
range		4-170	31-890	8-987	78-1,289
POTR/FETH	5				
mean		11	497	710	1,218
SE		6	168	472	576
range		0-35	88-873	65-2,584	448-3,492
POTR/SIHY	5				
mean		10	241	222	472
SE		4	104	63	94
range		3-26	7-485	26-330	319-823
POTR/BRCA	5				
mean		53	558	608	1,219
SE		40	156	196	254
range		0-212	104-970	56-1,201	371-1,877
POTR/POPR	8				
mean		41	456	283	780
SE		16	132	52	120
range		0-117	31-947	17-426	303-1,287
POTR-ABLA/AMAL	6				
mean		670	449	138	1,256
SE		285	106	53	225
range		127-1,642	164-823	12-317	578-1,986
POTR-ABLA/SYOR/SESE	13				
mean		235	594	174	1,004
SE		49	94	70	140
range		22-575	66-1,400	2-742	202-2,121
POTR-ABLA/SYOR/CAGE	3				
mean		205	452	120	777
SE		109	247	7	186
range		32-408	131-938	108-131	437-1,079
POTR-ABLA/JUCO	12				
mean		127	134	113	374
SE		74	40	46	89
range		7-911	4-411	2-490	78-1,139

(con.)

APPENDIX D2. (Con.)

Community type	N[1]	Shrubs	Forbs	Graminoids	Total
			Lb/acre		
POTR-ABLA/SESE	46				
mean		22	532	214	767
SE		5	61	44	73
range		0-153	36-2,174	1-1,479	69-2,289
POTR-ABLA/CAGE	31				
mean		5	168	98	271
SE		1	32	25	46
range		0-22	1-705	1-601	3-915
POTR-ABCO/SYOR	7				
mean		165	193	64	422
SE		26	70	44	108
range		69-275	15-518	2-311	188-1,036
POTR-PSME/AMAL	4				
mean		287	307	154	748
SE		112	51	89	97
range		16-547	191-398	6-402	561-994
POTR-PIPO/QUGA	1				
mean		212	248	248	707
SE		—	—	—	—
range		—	—	—	—
POTR-PIPO/JUCO	1				
mean		86	64	278	428
SE		—	—	—	—
range		—	—	—	—
POTR-PICO/JUCO	5				
mean		47	426	130	603
SE		28	109	37	87
range		6-157	15-659	31-255	290-824

[1]Number of intensively sampled stands.

APPENDIX E: PROPORTION OF YEARLY UNDERGROWTH PRODUCTION IN DIFFERENT VEGETATION CATEGORIES BY ASPEN COMMUNITY TYPES, AND THE SUITABILITY OF THIS UNDERGROWTH AS LIVESTOCK FORAGE

Community type	Vegetation categories			Forage suitability[1]		
	Shrubs	Forbs	Graminoids	Desirable	Intermediate	Least
	Percent					
POTR/ACGR/PTAQ	6	87	7	35	29	36
POTR/PRVI/SESE	30	48	22	55	40	5
POTR/PRVI/CAGE	46	25	29	55	41	4
POTR/SARA	35	52	13	52	37	11
POTR/SYOR/SESE	20	55	25	51	37	12
POTR/SYOR/CAGE	23	44	33	51	40	9
POTR/SYOR/FETH	56	27	17	52	45	3
POTR/JUCO/CAGE	24	34	42	53	38	9
POTR/JUCO/SIHY	—	—	—	46	47	7
POTR/SYOR/BRCA	12	29	59	46	51	3
POTR/SYOR/POPR	33	34	33	30	65	5
POTR/JUCO/ASMI	—	—	—	27	53	20
POTR/VECA	1	34	65	33	26	41
POTR/HELA	16	76	8	57	28	15
POTR/PTAQ	2	91	7	26	27	48
POTR/SESE	3	72	25	48	31	21
POTR/CAGE	4	41	55	57	36	7
POTR/FETH	1	41	58	47	42	11
POTR/SIHY	2	51	47	62	33	5
POTR/BRCA	4	46	50	35	60	5
POTR/POPR	5	58	37	29	69	2
POTR-ABLA/VACA	—	—	—	37	63	0
POTR-ABLA/AMAL	53	36	11	62	35	3
POTR-ABLA/SYOR/SESE	23	59	18	54	35	11
POTR-ABLA/SYOR/CAGE	26	58	16	55	36	9
POTR-ABLA/JUCO	34	36	30	45	48	7
POTR-ABLA/SESE	3	69	28	55	34	11
POTR-ABLA/CAGE	2	62	36	51	45	4
POTR-ABCO/SYOR	39	46	15	51	44	5
POTR-ABCO/JUCO	—	—	—	41	55	4
POTR-PSME/AMAL	38	41	21	45	47	8
POTR-PSME/JUCO	—	—	—	41	48	11
POTR-PIPO/QUGA	30	35	35	50	42	8
POTR-PIPO/JUCO	20	15	65	55	43	2
POTR-PICO/VASC	—	—	—	58	39	3
POTR-PICO/JUCO	8	71	21	44	51	5

[1]Based on proportionate canopy cover in suitability classes described by USDA Forest Service (1981).

APPENDIX F: PROPORTION OF ASPEN STANDS SAMPLED IN EACH OF UTAH'S NATIONAL FORESTS THAT WERE CLASSIFIED IN DIFFERENT ASPEN COMMUNITY TYPES

Community types	National Forests						All forests
	Wasatch-Cache	Ashley	Uinta	Manti-LaSal	Fishlake	Dixie	
(No. of stands classified)	(399)	(115)	(240)	(144)	(125)	(156)	(1,179)
	Percent						
POTR/ACGR/PTAQ	2	1	1	0	0	1	1
POTR/PRVI/SESE	19	0	13	4	1	0	10
POTR/PRVI/CAGE	1	2	1	1	0	1	1
POTR/SARA	1	0	2	5	1	0	1
POTR/SYOR/SESE	14	0	27	15	6	0	13
POTR/SYOR/CAGE	1	10	5	10	8	6	5
POTR/SYOR/FETH	0	0	0	0	2	3	1
POTR/JUCO/CAGE	5	31	1	0	9	1	6
POTR/JUCO/SIHY	T[1]	5	T	1	6	2	2
POTR/SYOR/BRCA	2	2	0	1	0	0	1
POTR/SYOR/POPR	2	3	1	4	0	5	3
POTR/JUCO/ASMI	2	1	0	0	0	0	1
POTR/VECA	T	0	T	0	0	0	T
POTR/HELA	2	0	2	1	1	0	1
POTR/PTAQ	2	0	3	0	0	1	1
POTR/SESE	13	1	18	12	4	3	11
POTR/CAGE	3	4	3	5	8	5	4
POTR/FETH	0	0	0	0	5	5	1
POTR/SIHY	0	1	0	0	1	6	1
POTR/BRCA	1	0	1	4	2	0	1
POTR/POPR	T	3	T	3	2	3	1
POTR-ABLA/VACA	1	1	0	0	0	0	T
POTR-ABLA/AMAL	2	0	T	1	0	0	1
POTR-ABLA/SYOR/SESE	6	3	6	3	2	1	4
POTR-ABLA/SYOR/CAGE	T	2	T	3	2	1	1
POTR-ABLA/JUCO	1	4	0	0	10	9	3
POTR-ABLA/SESE	10	2	8	12	8	3	8
POTR-ABLA/CAGE	2	3	T	3	13	28	7
POTR-ABCO/SYOR	T	0	4	7	4	1	2
POTR-ABCO/JUCO	0	2	0	1	6	5	2
POTR-PSME/AMAL	2	0	1	1	0	0	1
POTR-PSME/JUCO	0	4	0	0	0	2	1
POTR-PIPO/QUGA	0	1	0	3	0	1	T
POTR-PIPO/JUCO	0	2	0	0	0	7	1
POTR-PICO/VASC	1	2	0	0	0	0	1
POTR-PICO/JUCO	4	10	T	0	0	0	2

[1]T = less than 0.5 percent.

APPENDIX G: UTAH ASPEN COMMUNITY TYPE FIELD FORM

STUDY: **DATE:** **EXAMINER:**

CANOPY COVER ESTIMATES:
Estimate cover of each species as:
- trace (T) if less than 0.5%
- to nearest 1% if less than 10%
- to nearest 5% if over 10%

Estimate cover of trees (over 1.4 m high) and reproduction (less than 1.4 m high) separately (e.g. 40/5).

TOPOGRAPHY
1-Ridge 4-Lower slope
2-Upper slope 5-Bench/flat
3-Mid slope 6-Stream bot.

CONFIGURATION
1-Convex 3-Concave
2-Straight 4-Undulate

Plot No.			
Meridian			
T,R,S			
Elevation			
Aspect			
% slope			
Topography			
Configuration			
Other:			

TREES Scientific Name	Abbreviation	Common Name	Canopy Cover %		
Abies concolor	ABCO	white fir	--- / ---	--- / ---	--- / ---
Abies lasiocarpa	ABLA	subalpine fir			
Picea engelmannii	PIEN	Engelmann spruce	--- / ---	--- / ---	--- / ---
Picea pungens	PIPU	blue spruce	- - / -	- / ---	--- / ---
Pinus contorta	PICO	lodgepole pine			
Pinus ponderosa	PIPO	ponderosa pine	--- / ---	--- / ---	--- / ---
Populus tremuloides	POTR	quaking aspen	--- / ---	--- / ---	- / -
Pseudotsuga menziesii	PSME	Douglas-fir			
SHRUBS					
Acer grandidentatum	ACGR	canyon maple			
Amelanchier alnifolia	AMAL	western serviceberry			
Artemisia tridentata	ARTR	big sagebrush			
Juniperus communis	JUCO	common juniper			
Prunus virginiana	PRVI	chokecherry			
Quercus gambelii	QUGA	Gambel oak			
Rubus parviflorus	RUPA	thimbleberry			
Sambucus cerulea	SACE	blue elder			
Sambucus racemosa	SARA	European elderberry			
Symphoricarpos oreophilus	SYOR	mountain snowberry			
Vaccinium caespitosum	VACA	dwarf blueberry			
Vaccinium scoparium	VASC	grouse whortleberry			
GRAMINOIDS					
Bromus carinatus	BRCA	mountain brome			
Calamagrostis rubescens	CARU	pinegrass			
Carex geyeri	CAGE	elk sedge			
Carex obtusata	CAOB	obtuse sedge			
Carex rossii	CARO	Ross sedge			
Elymus glaucus	ELGL	blue wildrye			
Festuca idahoensis	FEID	Idaho fescue			
Festuca thurberi	FETH	Thurber fescue			
Poa pratensis	POPR	Kentucky bluegrass			
Sitanion hystrix	SIHY	bottlebrush squirreltail			
Stipa comata	STCO	needle-and-thread			
Stipa lettermanii	STLE	Letterman needlegrass			
Stipa occidentalis	STOC	western needlegrass			
FORBS					
Agastache urticifolia	AGUR	nettleleaf giant hyssop			
Aster engelmannii	ASEN	Engelmann aster			
Astragalus miser	ASMI	weedy milkvetch			
Delphinium occidentale	DEOC	duncecap larkspur			
Heracleum lanatum	HELA	common cowparsnip			
Mertensia arizonica	MEAR	tall bluebell			
Osmorhiza occidentalis	OSOC	sweetanise			
Polemonium foliosissimum	POFO	leafy polemonium			
Pteridium aquilinum	PTAQ	brakenfern			
Rudbeckia occidentalis	RUOC	western coneflower			
Scrophularia lanceolata	SCLA	lanceleaf figwort			
Senecio serra	SESE	butterweed groundwel			
Taraxacum officinale	TAOF	common dandelion			
Valeriana occidentalis	VAOC	western valerian			
Veratrum californicum	VECA	California false-hellebore			

COVER TYPE				
COMMUNITY TYPE				

☆U.S. GOVERNMENT PRINTING OFFICE:1986— 676-039/20040

Mueggler, Walter F.; Campbell, Robert B., Jr. Aspen community types of Utah. Research Paper INT-362. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 69 p.

A vegetation classification for the aspen-dominated forests of Utah is based upon existing community structure and plant species composition. Included are 36 community types that occur within six cover-type categories. A diagnostic key using indicator species facilitates field identification of the community types. Vegetational composition, productivity, and successional status are included. Tables provide detailed comparisons of community types. The classification and descriptions are based upon data from over 1,200 aspen stands scattered across the six National Forests within Utah.

KEYWORDS: aspen forests, community types, vegetation classification, Utah, forest ecology

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

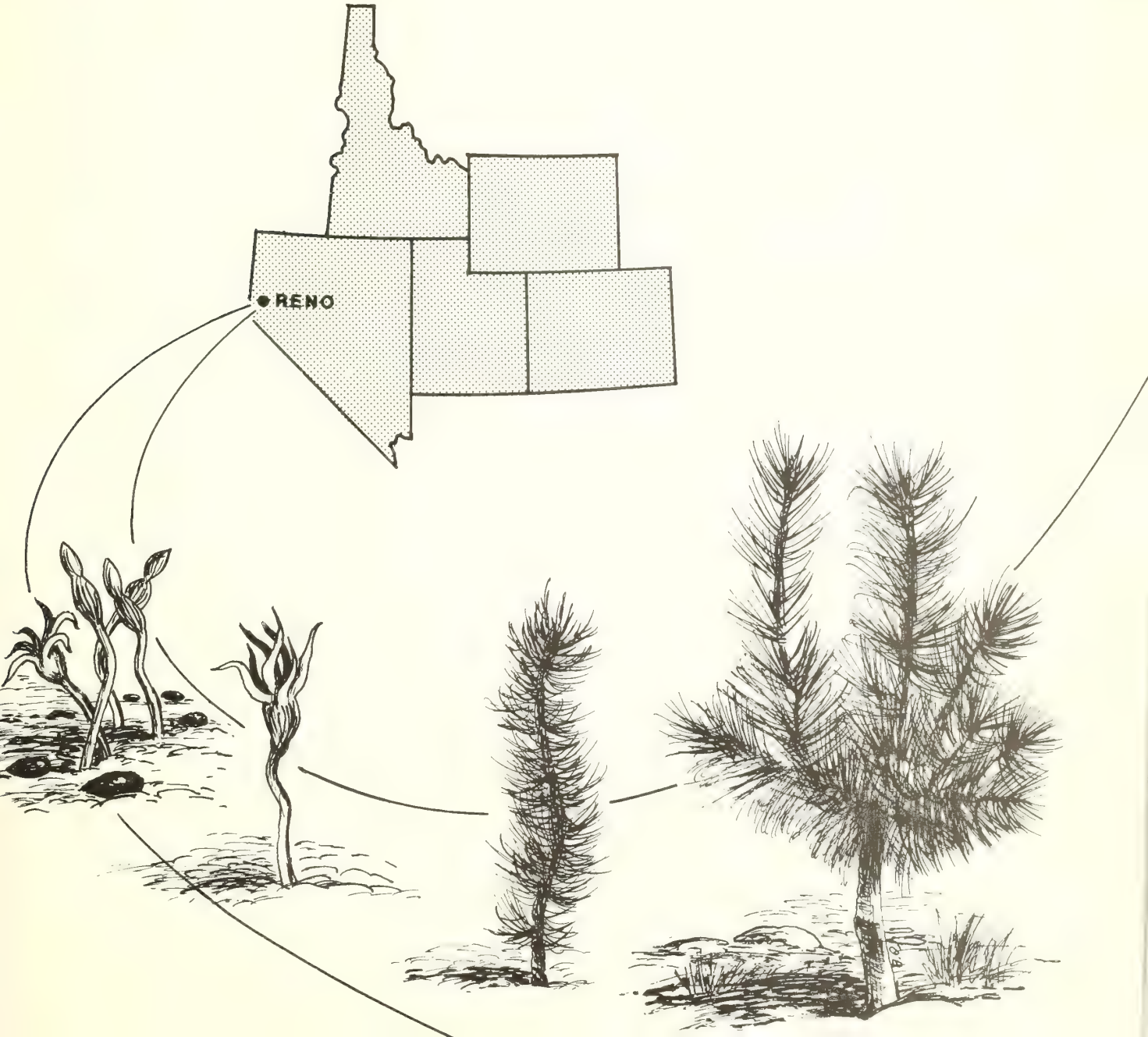
**Intermountain
Research Station
Ogden, UT 84401**

Research Paper
INT-363

April 1986

Pinyon Seedling Distribution Among Soil Surface Microsites

**Richard L. Everett
Susan Koniak
Jerry D. Budy**



THE AUTHORS

RICHARD L. EVERETT is a range scientist and Project Leader of the Intermountain Station's Pinyon-Juniper Ecology and Management research work unit in Reno. He has a B.S. degree in biology and an M.S. in range from the University of Nevada, Reno, and a Ph.D. degree in range ecology from Oregon State University, Corvallis.

SUSAN KONIAK was formerly a range scientist with the Intermountain Station's Pinyon-Juniper Ecology and Management research work unit. She has a B.S. degree in range management from the University of Nevada, Reno, and is completing requirements for an M.S. degree in biology at the University of Nevada, Reno.

JERRY D. BUDY is assistant professor of forestry in the Range, Wildlife and Forestry Department, Max C. Fleischmann College of Agriculture, University of Nevada, Reno. He has a B.S. degree from the University of Wisconsin, Madison, and a Ph.D. degree in forest hydrology from the University of Nevada, Reno.

RESEARCH SUMMARY

A highly variable number of pinyon seedlings ($\overline{X}$ = 5,480 seedlings/ha, CV = 126 percent) occurred in fully stocked singleleaf pinyon (*Pinus monophylla*)-Utah juniper (*Juniperus osteosperma*) stands. Pinyon seedlings were always more numerous (87 percent) on soil surface microsites adjacent to the tree than in the interspace between trees. Pinyon depends upon a standing crop of seedlings rather than soil seed reserves for species perpetuation. Seedling numbers rapidly decline following tree harvest. Seedlings in fully stocked stands may be of limited importance to species perpetuation because of tree longevity. But the concentration of seedlings in juxtaposition to the parent tree improves opportunities for management of natural regeneration by slash disposal or burn treatments.

Pinyon Seedling Distribution Among Soil Surface Microsites

Richard L. Everett
Susan Koniak
Jerry D. Budy

INTRODUCTION

Pinyon seedlings require a nurse plant for establishment. The nurse plant and seedling need not be the same species (Emmerson 1932), but in fully stocked stands this condition is highly probable. The enhancement of conifer seedling establishment in a microenvironment that ameliorates temperature and moisture extremes has been well documented (Youngberg 1965; Cochran 1973). In pygmy forests of the Southwest, seedlings of pinyon (*Pinus edulis*) and one-seed juniper (*Juniperus monosperma*) have been observed to occur in greater numbers under the tree crown for this reason (Meagher 1943; Johnsen 1962). Meagher did not measure seedling distribution patterns of pinyon, but he adequately demonstrated that shade and water increase rate of germination and survival of planted pinyon seed.

Little is known about singleleaf pinyon (*Pinus monophylla*) seedling numbers and their distribution within stands. Such information is important to land managers who must consider tree regeneration in balancing forage and wood product resources of these woodlands. An extensive preliminary study was, therefore, undertaken to provide baseline data for the number and distribution of singleleaf pinyon seedlings in fully stocked stands within the Great Basin.

METHODS

Square study plots, 20 m to a side, were established on 10 fully stocked stands in Nevada on various aspects at elevations of 2 030 m to 2 200 m. Fully stocked stands are defined by the Society of American Foresters (1958) as those stands where tree species effectively occupy all growing space. The soil surface within stands is heterogeneous and was classified into three general soil surface microsites—duff, transition, and interspace—based on percent needle cover and needle depth. Duff was defined as a soil surface microsite covered (at least 90 percent) by pinyon needles to a depth greater than 0.5 cm. Soil microsites having 20 to 90 percent of the soil surface covered by needles with an average depth less than 0.5 cm were defined as transition. Interspace soil microsites were characterized by less than 20 percent needle cover of less than 0.5-cm depth.

A series of five transects, 20 m in length, were laid out parallel to each other cross-slope at 5-m intervals across each study plot. Tree cover was determined by line intercept (Canfield 1941). Understory cover, number of pinyon seedlings (juveniles with a crown area less than 25 cm^2 and a height less than 30 cm), and the soil surface microsite were recorded within a 50- by 50-cm frame placed at every meter mark on the transects.

To determine seedling distribution from the tree bole, five pairs of trees were randomly selected for tree-to-tree transects in each study plot. Paired trees were greater than 20 cm in diameter (at stump height) and had at least 1 m of interspace between them. A series of 50- by 50-cm frames were laid down contiguously from tree bole to tree bole and understory cover, pinyon seedling numbers, and soil surface microsite recorded within each frame.

Numbers of seedlings found in parallel and tree-to-tree transects were totaled separately on each soil surface microsite for each study site. The percentage of the total seedlings within each soil microsite and the number of seedlings per square meter of soil surface microsite was determined for the 10 study sites and analyzed separately in one-way analysis of variance tests. An arcsine transformation was used on percentages to give a more normal distribution pattern to the data. Significant differences ($P = 0.05$) among means were determined using Hartley's sequential methods of testing (Snedecor 1956).

RESULTS AND DISCUSSION

Sampled stands were dominated by singleleaf pinyon with lesser amounts of Utah juniper (*Juniperus osteosperma*). Tree cover varied from 26 to 63 percent of the ground surface on the 10 study sites. Understory cover on all study sites was less than 8 percent. A total of 137 singleleaf pinyon seedlings were recorded in the parallel transects and 78 seedlings in the tree-to-tree transects. Mean seedling density across all sites was estimated at 0.5 seedlings/m^2 but varied from 0 to 2.28 among sites.

The estimated mean number of singleleaf pinyon seedlings per hectare was large ($\bar{X} = 5{,}480$) but highly variable (CV = 126 percent) among sampled stands. More pinyon seedlings occurred in the duff than in transition or interspace soil surface microsites on all sites. The duff microsite occupied the greatest portion of the soil surfaces, but the number of seedlings was disproportionately higher than would be expected by chance location (table 1). The majority (87 ± 18 percent) of seedlings occurred under or adjacent to the tree crown (table 1) as reported for *Juniperus monosperma* seedlings (84 percent) in Arizona woodlands (Johnsen 1962). The preponderance of seedlings near the parent plant suggests that safe sites for seedling establishment are sparse (Horn

1981). The number and location of safe sites control the size and the distribution of pinyon seedling populations.

Estimates showed that both parallel and tree-to-tree transects had greater seedling density in the duff surface microsite (table 1). Differences in seedling density estimates between transect types occurred and may be the result of sampling only larger trees in tree-to-tree transects. Nevertheless, the duff microsite appears more favorable for seedling establishment, a response opposite that observed for most understory species (Everett and Koniak 1982). Understory provided little or no cover ($\bar{X}$ = 2.6 percent ground cover; CV = 130 percent) on microsites containing seedlings.

Table 1.—Proportion of total pinyon seedlings (percent) and seedling density (m^2) in the soil microsites and the proportion of sample area occupied by each soil microsite for all sites

	Soil microsite		
	Duff	Transition	Interspace
Parallel transects			
Percent of total			
Microsite	46.9[a,1]	24.3[b]	28.8[b]
Seedlings	83.0[a]	4.1[b]	12.9[b]
Seedling density	.95[a]	19[b]	.31[b]
Tree-to-tree transects			
Percent of total			
Microsite	50.2[a]	23.3[b]	26.0[b]
Seedlings	67.0[a]	17.0[b]	17.0[b]
Seedling density	.72	.41	.34

[1]Significant differences (P = 0.05) in rows denoted by superscripts

Total number of seedlings (78) encountered in tree-to-tree transects is marginal for reliable estimates of pinyon seedling distribution from the tree bole, but seedling density definitely decreases with distance from the tree bole and especially at the duff edge (table 1 and fig. 1). The 150- to 200-cm distance class encompasses the average duff radii (167 cm) of the sample trees. Duff is shallow at the crown edge, increasing in depth under the crown, and often decreasing in depth immediately adjacent the tree bole. In duff, the germinating seed can establish root-mineral soil contact in a microenvironment less prone to desiccate the root tip as it emerges from the seed hull (our own observations; Lanner 1981).

Pinyon seedlings appear of limited importance for species perpetuation in fully stocked stands. On fire-safe sites, large trees rarely die and they monopolize site resources over a long life span, 350 years (Meeuwig 1979; Meeuwig and Cooper 1981). Most seedlings have only a short time in which to succeed or perish because of annual summer drought and sporadic drought years. When stands burn, fires consume both duff and seedlings. No pinyon seedlings were recorded on prescribed burns of pinyon-juniper woodlands for 5 years following fire (Everett and Ward 1984). Seedlings may represent the germinating surplus seed of an efficient dispersing system. The large, nutritious seeds of pinyon encourage their harvest and dispersal by both rodents and birds (Emmerson 1932; Vander Wall and Balda 1977; Ligon 1978; Lanner and Vander Wall 1980; Lanner 1981).

The concentration of pinyon seedlings under the crown provides management with an opportunity to enhance or discourage natural pinyon regeneration. If regeneration is to be curtailed, prescribed burning of stands or individual trees automatically eliminates a majority of the standing seedling crop. Exposing seedlings to the full sunlight reduces seedling survival significantly. Seedling survival on 10 tree harvest sites declined from a preharvest total of 100 to seven and then one in the first and third years following tree harvest. On four adjacent uncut sites, seedlings increased from eight to 20 the first and third years following tree harvest. After tree harvest, a moderate slash cover may be applied to increase seedling survival (Meeuwig and Bassett 1983).

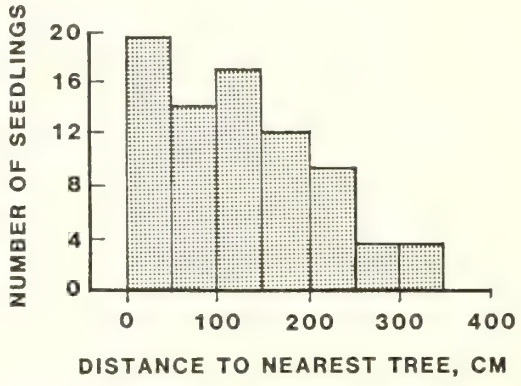


Figure 1.—Distribution of pinyon seedlings in distance classes from the nearest tree. (The 150- to 200-cm distance class encompasses the mean duff radii [$\bar{X}$ = 167 cm]).

REFERENCES

Canfield, R. H. Application of the line interception method in sampling range vegetation. Journal of Forestry. 39: 388-394; 1941.

Cochran, P. H. Natural regeneration of lodgepole pine in south-central Oregon. Research Note PNW-204. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1973. 18 p.

Emmerson, F. W. The tension zone between the grama grass and pinon-juniper associations in northeastern New Mexico. Ecology. 13: 347-359; 1932.

Everett, R. L.; Koniak, S. Understory vegetation in fully stocked pinyon-juniper stands. Great Basin Naturalist. 41: 467-475; 1982.

Everett, R. L.; Ward, K. Early plant succession on pinyon-juniper controlled burns. Northwest Science. 58: 57-67; 1984.

Horn, H. S. Some causes of variety in patterns of secondary succession. In: West, D. C.; Shugart, H. H.; Botkin, D. B., eds. Forest succession concepts and application. New York: Springer-Verlag; 1981: 24-35.

Johnsen, T. N. One-seed juniper invasion of northern Arizona grasslands. Ecological Monographs. 32: 187-207; 1962.

Lanner, R. M. The piñon pine: a natural and cultural history. Reno, NV: University of Nevada; 1981. 208 p.

Lanner, R. M.; Vander Wall, S. B. Dispersal of limber pine seed by Clark's nutcracker. Journal of Forestry. 78: 635-639; 1980.

Ligon, T. D. Reproductive interdependence of piñon jays and piñon pines. Ecological Monographs. 48: 111-126; 1978.

Meagher, P. S. Reaction of pinyon and juniper seedlings to artificial shade and supplementary watering. Journal of Forestry. 41: 480-482; 1943.

Meeuwig, R. O. Growth characteristics of pinyon-juniper stands in the Great Basin. Research Paper INT-228. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979. 22 p.

Meeuwig, R. O.; Bassett, R. L. Pinyon-juniper. In: Silvicultural systems for the major forest types of the United States. Agriculture Handbook 445. Washington, DC: U.S. Department of Agriculture, Forest Service; 1983: 84-86.

Meeuwig, R. O.; Cooper, S. V. Site quality and growth of pinyon-juniper stands in Nevada. Forest Science. 27: 583-601; 1981.

Snedecor, E. W. Statistical methods applied to experiments in agriculture and biology. Ames, IA: Iowa State University; 1956. 534 p.

Society of American Foresters. Forestry terminology. 3d ed., rev. Washington, DC: Society of American Foresters; 1958. 97 p.

Vander Wall, S. B.; Balda, R. P. Co-adaptations of the Clark's nutcracker and the piñon pine for efficient seed harvest and dispersal. Ecological Monographs. 47: 89-111; 1977.

Youngberg, C. T. Silvicultural benefits from brush. In: Proceedings, Society of American Foresters. Washington, DC: Society of American Foresters; 1965: 55-59.

Everett, Richard L.; Koniak, Susan; Budy, Jerry D. Pinyon seedling distribution among soil surface microsites. Research Paper INT-363. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 3 p.

A highly variable number of pinyon seedlings ($\overline{X}$ = 5,480 seedlings/ha, CV = 126 percent) occurred in fully stocked singleleaf pinyon *(Pinus monophylla)*-Utah juniper *(Juniperus osteosperma)* stands. Pinyon seedlings were always more numerous (87 percent) on soil surface microsites adjacent to the tree than in the interspace between trees. Pinyon depends upon a standing crop of seedlings rather than soil seed reserves for species perpetuation. Seedling numbers rapidly decline following tree harvest. Seedlings in fully stocked stands may be of limited importance to species perpetuation because of tree longevity. But the concentration of seedlings in juxtaposition to the parent tree improves opportunities for management of natural regeneration by slash disposal or burn treatments.

KEYWORDS: singleleaf pinyon, regeneration, stocking rate

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

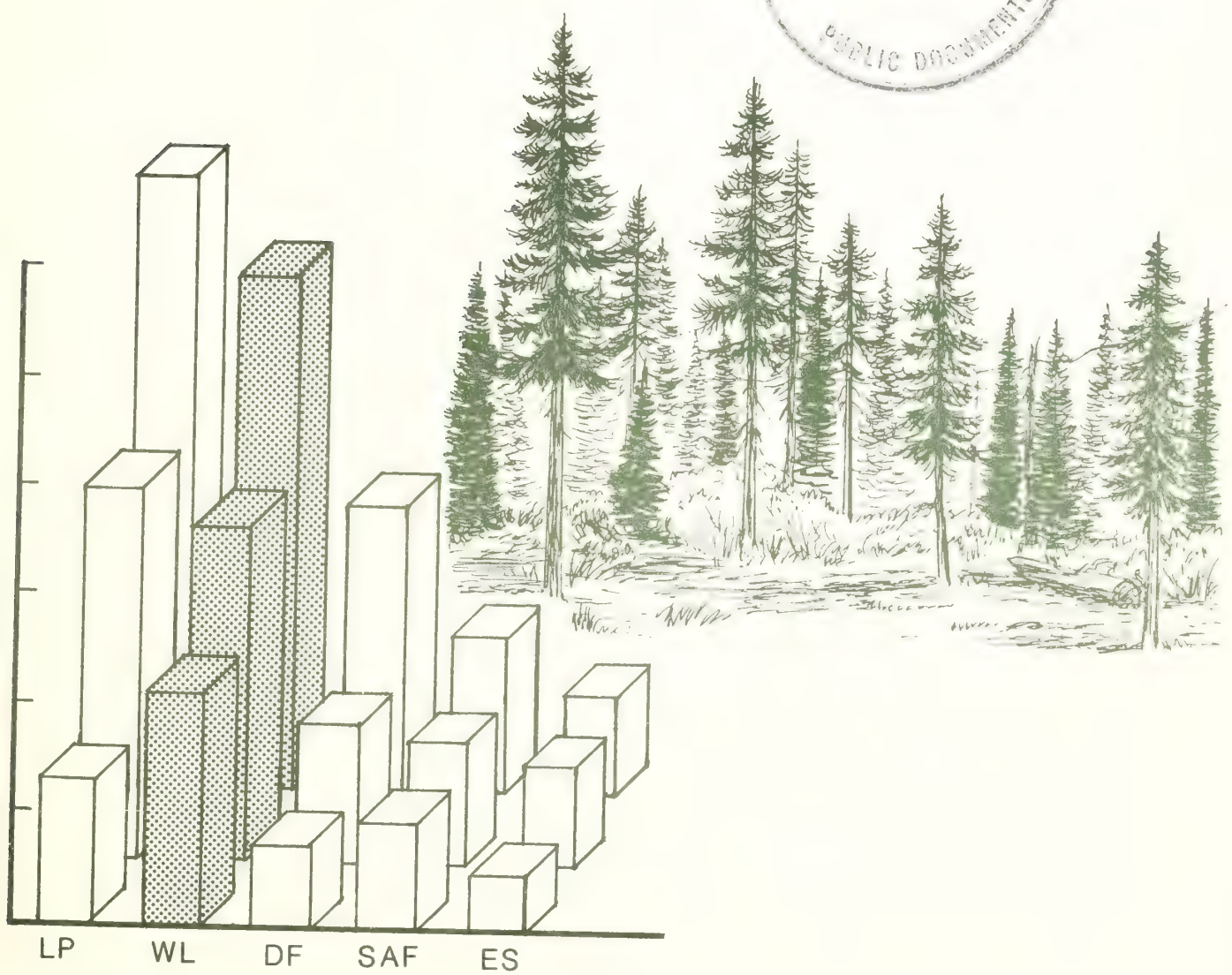
Research Paper
INT-364

June 1986

Site Treatments Influence Development of a Young Mixed-Species Western Larch Stand

Dennis M. Cole
Wyman C. Schmidt

AUG 28 1986
PUBLIC DOCUMENTS



THE AUTHORS

DENNIS M. COLE is a research silviculturist with the Silviculture of Conifers in Montane and Subalpine Forest Ecosystems of the Intermountain and Northern Rocky Mountain West research work unit at the Forestry Sciences Laboratory, Bozeman, MT. His studies have focused on lodgepole pine silviculture, particularly growth and yield relationships, culture of immature stands, and management of the species in the face of major insect and disease problems.

WYMAN C. SCHMIDT is a research silviculturist and Project Leader of the Silviculture of Conifers in Montane and Subalpine Ecosystems of the Intermountain and Northern Rocky Mountain West research work unit at the Forestry Sciences Laboratory, Bozeman, MT. Dr. Schmidt's research has focused on the ecology, regeneration processes, stand development, and related cultural practices in coniferous forests of the Intermountain West. Much of his research has centered on the interrelationships of timber, water, and other resources as well as the interaction of cultural practices with insect pests such as western spruce budworm.

ACKNOWLEDGMENTS

We gratefully acknowledge previous researchers involved in the initial planning, installation, and subsequent remeasurements of this study, including Kenneth N. Boe, Steven A. Haglund, Ward W. McCaughey, Arthur L. Roe, Jack A. Schmidt, Raymond C. Shearer, and Anthony E. Squillace.

July 1986
Intermountain Research Station
324 25th Street
Ogden, UT 84401

RESEARCH SUMMARY

This study evaluated the effects of site treatments on stand development after 25 years in the western larch (formerly western larch—Douglas-fir) forest cover type. Four site treatments (all combinations of leaving or removing residual understory and scarifying or not scarifying seedbeds) were imposed under a seed-tree harvest cutting. Larch established best on mineral soil but grew best where scarification was modest and where residual trees and shrubs had been slashed. Douglas-fir was less sensitive to site preparation in both establishment and growth. When comparisons were restricted to trees of good vigor, larch and lodgepole pine continued to grow substantially faster in height than their counterparts such as Douglas-fir, spruce, and subalpine fir on most treatments, but Douglas-fir height growth accelerated substantially from age 15 to 25. By age 25, the greater overstocking on scarified plots began taking its toll on western larch by reducing diameter growth and increasing mortality.

Site Treatments Influence Development of a young Mixed-Species Western Larch Stand

Dennis M. Cole
Wyman C. Schmidt

INTRODUCTION

More intensive management could be applied to many young stands in conifer forests of the Northern Rockies. Vast areas are stocked with stands that contain a mixture of conifer species. An important mixed species cover type in this region is the western larch type (formerly called the larch—Douglas-fir type)(Society of American Foresters 1980). It is usually dominated by western larch (*Larix occidentalis* Nutt.) and Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco); but also has appreciable amounts of Engelmann spruce (*Picea engelmanii* Parry) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). Species sometimes occurring in the cover type are lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.), western white pine (*Pinus monticola* Dougl.), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western redcedar (*Thuja plicata* Donn ex D. Don). The exact species composition in the western larch type is determined largely by the successional stage of the stand and the physical environment in which the stand occurs. Usually the above-mentioned mixture of conifer species occurs in habitat types of the *Pseudotsuga menziesii* and *Abies lasiocarpa* successional series (Daubenmire and Daubenmire 1968; Pfister and others 1977).

Mature and overmature forests of the western larch type, containing appreciable amounts of larch, Douglas-fir, spruce, and white pine in the overstory, have long been sought for timber harvest. Many of the accessible mature stands have been harvested and regenerated to young mixed-species stands that show the influence of the particular cutting system and site preparation methods that were used. Knowledge of the effects on future stands of cutting systems and various site preparation and vegetation-manipulation treatments is an important consideration for proper management of stands still to be harvested.

Because of its rapid growth, excellent wood, desirable esthetic qualities, and low incidence of insect attacks, disease, and defects, western larch is usually featured in management of the western larch type. But because most managers seek to maintain a mixture of species, Douglas-fir, Engelmann spruce, and lodgepole pine are also encouraged in the regeneration process. These objectives usually result in even-age management of stands of the western larch type, including either clearcutting, shelterwood, or seed-tree methods of regeneration (Schmidt and others 1976). Each of these cutting methods can provide favorable conditions for natural regeneration of the favored species—but depending on seedbed and understory vegetation conditions following cutting, the composition, density, and growth of the future stand can vary widely (Polk and Boe 1951; Roe 1955; Schmidt 1969).

Polk and Boe (1951) and Roe (1955) concluded that desired composition of the future stand can neither be attained nor maintained through cutting method alone; seedbed preparation and later stand improvement practices are necessary. Specifically, practices are required that obtain establishment of desired tree species before shrubs and other vegetation overwhelm the site. Roe (1955) studied the relative need for sunlight and mineral-soil seedbeds of larch and its common associates in the western larch type at Terrace Hill on the Coram Experimental Forest in northwestern Montana. He described the relationships among method of cutting, proportion of ground surface in favorable seedbed, and resultant stocking percentages of each species.

Schmidt (1969) later reported on seedling and early sapling development and concluded that site preparation—in the form of mechanical scarification, prescribed burning, and slashing of competing shrubs—influenced not only regeneration establishment, but subsequent seedling development. He found, after 12 to 15 years, that larch regenerated abundantly, grew rapidly, and became dominant where prescribed burning or mechanical scarification provided a sufficient area of ash or mineral soil seedbeds and reduced the amount of competing vegetation. Spruce seedlings also required mineral soil for successful establishment but grew slowly on the exposed seedbeds favored by larch. In contrast, Douglas-fir was insensitive to seedbed condition in the regeneration phase, but tended to dominate the stands where seedbeds had little or no preparation and larch competition was light.

From the above observations, Schmidt (1969) predicted that the direct effects of seedbed and understory would continue to diminish and the effects from differences in stand density and shade tolerance would increase as the stand grew past the early sapling stage. This report tests this hypothesis by comparing subsequent growth patterns against site treatments in the 25-year-old stand.

STUDY DESCRIPTION AND PROCEDURES

This study was established at Terrace Hill on Coram Experimental Forest in northwestern Montana within a large, recently logged stand of western larch and Douglas-fir. The stand was located on a lower northeast slope and had a larch site index of 58 ft at 50 years—a medium site. The original stand consisted primarily of western larch (WL) and Douglas-fir (DF), but contained small numbers of spruce (ES), western white pine (WWP), lodgepole pine (LP), subalpine fir (SAF), and western hemlock (WH). The stand was logged in 1943, leaving about five healthy, well-distributed dominant larch seed trees per acre and a heavy residual understory of trees (chiefly subalpine fir and tall shrubs such as yew [*Taxus brevifolia* Nutt.]). Slash was piled and burned in 1944. In 1945, the residual understory of trees and tall shrubs was slashed on an area of 8 acres and an equal-size area left unslashed. The ground surface after logging and burning included undisturbed forest floor and mineral soil exposed by tractor skidding, road construction, and slash burning. These operations left four generalized combinations of seedbed-vegetative competition conditions for study: (1) unslashed-unscarified, (2) unslashed-scarified (scarified only), (3) slashed-unscarified (slashed only), and (4) slashed-scarified. It is important to understand that unslashed and unscarified treatments still received some soil disturbance in the course of the logging process.

Fifteen milacre (0.0004-ha) plots were randomly established for each of the four seedbed/competing vegetation conditions, making a total of 60 sample plots. In 1949, after several years had been allowed for adequate seedfall, reproduction was tallied by species. Following the reproduction tallies, the study was converted to a stand development study and the initial seedling establishment and early seedling development results were reported (Roe 1955). Upon conversion to a stand development study, all tree seedlings on the milacre study plots were recorded by species and measured for height to the nearest 0.1 ft (3 cm) and their vigor subjectively classified as good, fair, or poor, on the basis of crown length and density, needle color and length, and prior growth. As the trees grew into and beyond the sapling stage at the third and fourth measurements, crown class of trees on the milacre plots was also recorded. At the fourth measurement at 25 years, diameter at breast height (d.b.h.) was also measured on all trees exceeding 4.5 ft (1.37 m) in height.

Data from this completely randomized study were subjected to analysis of covariance to determine the statistical significance of treatments on growth of the different species. Trees-per-acre stocking at establishment in 1949 was used as the covariate in these analyses. Trends in stocking, composition, vigor, and dominance were also analyzed.

RESULTS

A brief review of the 15-year results shows that the seed trees, adjacent timber, and small understory trees left after logging produced enough seed to adequately stock, and in most cases overstock, the study area. The mineral soil seedbeds were especially overstocked, primarily with larch and spruce (Schmidt 1969). Non-scarified forest floor seedbeds had only about one-third the stocking of the mineral soil seedbeds and had higher proportions of Douglas-fir and subalpine fir in comparison to larch and spruce. These treatment-related differences in stocking density and composition provided the basis for earlier forecasts of significant differences among the species in future survival, growth, vigor, and relative expression of dominance in the stand (Schmidt 1969).

The earlier report (Schmidt 1969) of growth differences among species featured dominant trees, but after 25 years many dominant sample trees were dead. Therefore, growth results presented here are in terms of all trees surviving on the quadrats at the last measurement. Height growth from 15 to 25 years of age and breast height diameter at 25 years of age were analyzed for the major species regenerated in the study area: western larch, lodgepole pine, Douglas-fir, Engelmann spruce, and subalpine fir. With the additional 10 years of stand development, growth effects have become more evident, earlier conclusions can be tested, and still stronger inferences for future stand development can be made.

Diameter Growth

Several treatments had produced no Engelmann spruce or subalpine fir of breast height at the time of the last measurement; therefore only western larch and Douglas-fir were analyzed for diameter growth differences among species and treatments. Treatment effects differed significantly ($p=0.05$) between western larch and Douglas-fir. Scarification resulted in greater diameters among western larch than Douglas-fir (fig. 1). Slashing promoted growth of larch more than Douglas-fir, but only on unscarified plots (fig. 1). The largest diameters were registered for larch on unscarified, slashed plots; the smallest diameters were also larch, but where no slashing or scarification had occurred. The slow diameter growth of larch in unscarified areas likely results from the intolerance of larch to competition from overtopping residual vegetation in the unslashed plots. The rapid diameter growth of larch is likely a consequence of limiting competition by slashing but not scarifying seedbeds.

In contrast to larch, slashing on unscarified plots reduced diameter growth of Douglas-fir. This effect seems to be related to the strong growth performance of the larch; the higher densities and faster growth of larch apparently suppress diameter growth of Douglas-fir established at the same time. Slashing had virtually no effect on either larch or Douglas-fir on scarified plots.

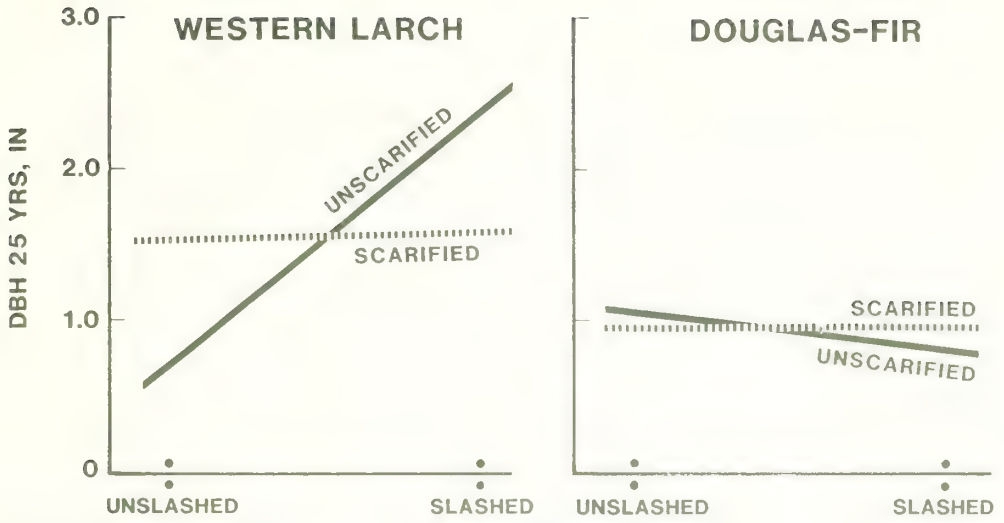


Figure 1.—Effect of scarification and slashing on diameter growth to 25 years of age.

Height Growth

Height growth differences among western larch, Douglas-fir, Engelmann spruce, and subalpine fir were not significant when adjusted for stand density, but treatments did significantly affect ($p=0.05$) height growth of all species (fig. 2). Slashing of understory shrubs and trees left after the seed tree harvest resulted in significantly greater height growth of regeneration than when left unslashed, while scarification significantly reduced height growth only in plots where slashing had occurred. The best height growth occurred where no scarification occurred but where residual trees and shrubs were slashed. In contrast, the poorest height growth occurred where scarification had occurred, but where no slashing was done.

Seedling vigor—classified on the basis of early growth, foliage density, and needle color and length—was a good indicator of subsequent height growth in earlier measurements of this study (Schmidt 1969). For example, from age 10 to 15, good-vigor larch, lodgepole pine, Douglas-fir, and subalpine fir grew about two and six times faster than their fair-vigor and poor-vigor counterparts. Good-vigor spruce grew only about twice as fast as their poor-vigor counterparts. Each vigor class of western larch and lodgepole pine grew about twice as fast as other species of corresponding vigor classes during that period.

Tree vigor at the last measurement was again considered as a means of evaluating height growth. A discriminant analysis was made to determine whether vigor could be classified using species and treatment variables; however, no effective discriminator involving treatments was found. Therefore, vigor was evaluated as before as an influence on growth, irrespective of treatments.

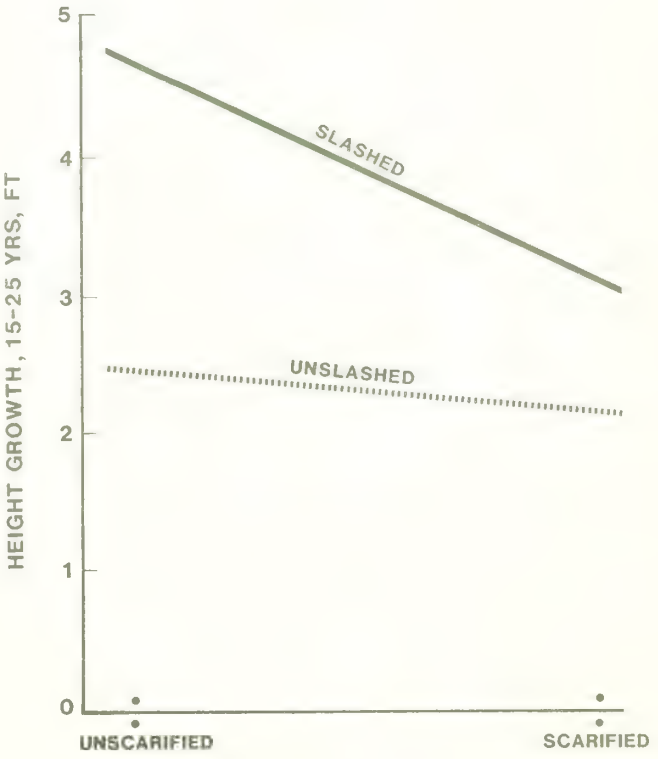


Figure 2.—Effect of scarification and slashing on height growth of major species from age 15 to 25 years.

The same general height growth relationships apparent in the 10- to 15-year age period among and between species and vigor classes were also apparent in the 15- to 25-year age period (fig. 3). On the basis of average periodic annual increment (PAI), however, growth rate differences of the good-vigor class lessened for most species, as did differences between species within the same vigor class. Douglas-fir was the exception; trees in the good-vigor class at 15 years of age increased in height PAI from 15 to 25 years of age, suggesting that favorably located Douglas-fir seedlings of good vigor can be expected to gradually increase their growth rate and maintain their vigor in the first 25 years of stand development. The two seral species, larch and lodgepole pine, continued to exceed other species in rate of height growth, but trees originally noted for good vigor grew substantially slower from age 15 to 25 than they had from age 10 to 15. Differences in PAI between the two growth periods were less apparent and less consistent for the fair and poor vigor trees. Major seral species, in particular, were influenced in the regeneration stage by seedbed conditions and competing vegetation; with time this becomes less important than intertree competition.

A composite of the total 25-year period shows the two seral species—lodgepole pine and western larch—making the greatest total height growth (fig. 4). Even the fair-vigor lodgepole pine and western larch had greater height growth than the good-vigor trees of all other species, but the good-vigor Douglas-fir were accelerating. The shade-tolerant subalpine fir and spruce lagged behind in keeping with their normal understory positions in this forest type. How differential species performance influenced the character of the stand at age 25 is discussed in the following section.

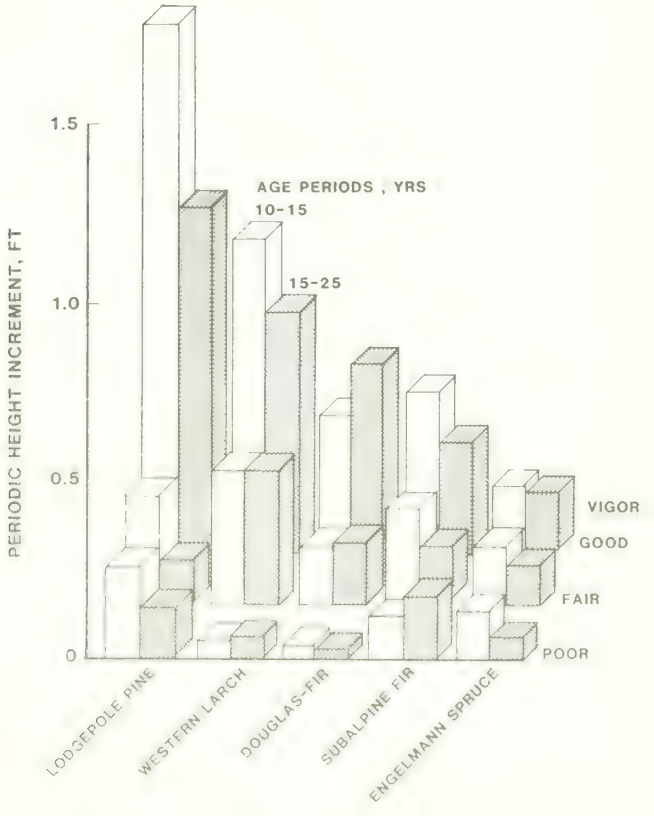


Figure 3.—Periodic annual height increment for the age periods 10 to 15 and 15 to 25 of five conifers in three different vigor classes.

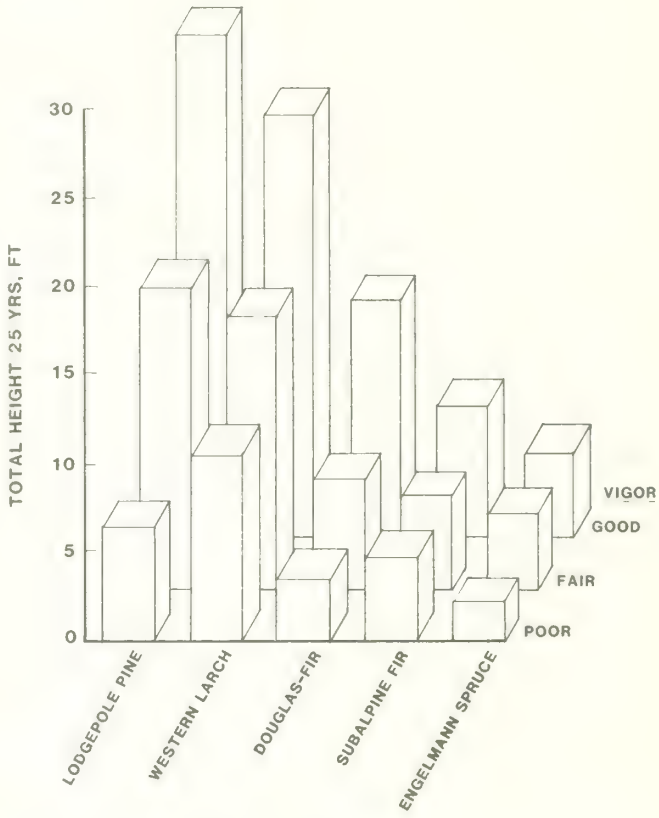


Figure 4.—Total height at age 25 of five different conifers in three different vigor classes.

Stand Character

Western larch and spruce comprised two-thirds or more of the large number of trees per acre established on seedbeds that had been scarified; Douglas-fir and subalpine fir comprised about two-thirds of the less-dense regeneration in the treatments where the forest floor was unscarified (Schmidt 1969). But total stand density, species stocking frequency, and stocking frequency of dominant trees have changed markedly during the 25 years of study (table 1). Where the forest floor was not scarified, initially modest stand densities increased by about 1,000 trees per acre. Where scarified, stand densities increased substantially where understory had not been slashed—apparently due to continued regeneration of the more tolerant species from the residual seed source. Where scarified and slashed, stand density peaked at age 15 but by age 25 declined below the density at age 10, due mainly to mortality of western larch from interspecies competition. At age 15, larch

Table 1.—Stand density and stocking frequency of all trees and dominants by age and treatment

Treatment	Age	Density of regeneration	Stocking frequency				
			WL[1]	DF	ES	SAF	Other[2]
		Trees/acre	*Percent*				
Unslashed, unscarified	10	3,140	[3]33(33)	67(53)	7(0)	20(7)	(7)
	15	4,210	40(40)	73(40)	13(0)	20(7)	(13)
	25	4,267	40(40)	73(36)	7(0)	33(7)	(17)
Unslashed, scarified	10	13,390	100(93)	80(0)	80(0)	60(0)	(7)
	15	17,330	100(93)	80(0)	100(0)	87(0)	(7)
	25	16,733	87(67)	73(13)	93(0)	80(0)	(20)
Slashed, unscarified	10	3,270	67(47)	73(53)	20(0)	33(0)	(0)
	15	4,410	73(47)	67(46)	40(0)	33(0)	(7)
	25	4,067	53(33)	67(40)	47(0)	33(0)	(7)
Slashed, scarified	10	10,470	93(73)	80(13)	73(0)	7(0)	(14)
	15	12,800	87(66)	80(7)	80(0)	20(0)	(27)
	25	9,467	87(59)	67(7)	80(0)	20(0)	(34)

[1]Relative shade tolerance ranking of species is from left to right, least (WL) to most (SAF).
[2]Other species were primarily lodgepole pine and a few western white pine.
[3]Frequencies in parentheses are the percentages of milacre quadrats in which dominant trees of the species occur.

occurred uniformly on scarified areas and dominated up to 90 percent of such areas, but by age 25 their stocking distribution had declined and they dominated only about two-thirds of scarified area. Most of the decline in larch dominance on scarified seedbeds occurred where competitive shrubs and understory trees were not removed. Larch only stocked 40 to 50 percent of the unscarified areas, but where they were able to establish, they usually became dominant.

Like larch, spruce was well-distributed, stocking at least 50 percent of the area where slashing had occurred and over 80 percent of the area where scarification had occurred. Because of its slow juvenile growth, spruce was overtopped by other species and exhibited no dominance in any treatment.

Douglas-fir was well-distributed at age 25, indicating little establishment preference for any treatment. In unscarified treatments, Douglas-fir was able to express dominance about equally with larch, apparently because of significantly lower larch stocking densities there; but it expressed little dominance in scarified areas where larch and lodgepole pine dominated.

Tree Vigor

Considering the treatment-related differences in stocking and dominance, changes in the relative vigor status of the species were expected. Initially larch, Douglas-fir, spruce, and subalpine fir each had about 60 percent of seedlings classified as good vigor, but by age 25 each except subalpine fir had declined to about 30 percent high-vigor trees. Overstocking was taking its toll on vigor.

The vigor of subalpine fir increased slightly to about 65 percent classified as good vigor. This slight increase occurred on the scarified-only treatment, but was offset by a similar decrease on the treatments where slashing had occurred. These effects are consistent with the relative shade tolerance ranking of subalpine fir.

At 25 years of age, more than three-fourths of the good-vigor larch occurred on the treatments receiving scarification. Conversely, the percentage of poor-vigor larch there increased from 5 to over 25 percent. More than three-fourths of poor-vigor larch occurred on scarified plots—an apparent consequence of the high stand densities on scarified treatments.

The reduction in numbers of good-vigor spruce at age 25 occurred almost exclusively on scarified treatments, even though such sites supported nearly all of the remaining good-vigor spruce. Like larch, these reductions in vigor indicate that the heavy stand densities in the scarified treatment areas reduce spruce vigor, despite the encouragement of spruce establishment by scarification.

Initially, good-vigor Douglas-fir occurred at about the same frequency on all treatments, but by age 25, two-thirds of the good-vigor Douglas-fir were found on unscarified treatments. Poor-vigor Douglas-fir increased from 10 percent to more than 35 percent of trees at age 25. The highest proportion of good-vigor trees and the lowest proportion of poor-vigor trees occurred on the slashed-only treatment.

DISCUSSION AND CONCLUSIONS

The Terrace Hill study demonstrates that seed-tree cutting in the western larch type allows considerable flexibility in guiding the composition and development of the new stand, depending on seedbed and understory vegetation treatment in the establishment phase. It also demonstrates the consequences of failing to control density through the late sapling-early pole stage—in terms of height and diameter growth, dominance, and vigor.

As pointed out earlier (Schmidt 1969), precise regulation of stocking is difficult in natural regeneration systems because of yearly variations in seed production, germination, and seedling survival among species; therefore, cleaning or thinning in the sapling stage assumes critical importance for guiding the composition and growth of the future stand. Because this study was neither thinned nor cleaned, the known benefits of these practices for furthering stand development and management objectives could not be quantified. On the other hand, at age 15 longer term consequences of the overstocking on the different species could only be speculated upon by extrapolating trends in the first 15 years of stand development. The additional 10 years of natural stand development to age 25 provided a better basis for testing of earlier conclusions on the apparent course of mixed species stand development in overstocked natural regeneration in the western larch type.

Results of this study to age 15 suggested that where there had been little or no scarification or removal of understory vegetation, intolerant species—especially larch—were disadvantaged and expected to decline further in vigor and generally be poor prospects for future management. At age 25, this expectation is less clear. Western larch and lodgepole pine, both very shade-intolerant species, have maintained their relative positions of dominance and growth in the stand even where no scarification or removal of competing understory vegetation occurred. Apparently, once established with other species in the western larch type, larch are able to express dominance as well or better than other species. This is not to suggest that choice and timing of seedbed and competing vegetation treatments is not important. Composition and relative growth of the different species are strongly affected by seedbed and competing vegetation conditions and their resultant stand density effects.

From a management perspective, considerable flexibility is provided managers by seed-tree cutting in this forest type, when seedbed and vegetation conditions are manipulated in the regeneration process. If the objective is to maximize timber production on a short rotation, scarification and removal of competing vegetation will ensure prompt and predominant larch regeneration with significant representation of spruce and Douglas-fir. But growth rates will not meet short rotation objectives unless stand density is controlled at an early age. Because larch and lodgepole pine have regeneration and growth advantages on disturbed sites, they have strong timber production advantages; but the beginning of growth decline due to overstocking during the 15- to 25-year age period demonstrates the need for early cleaning and spacing to enhance vigor and growth. On the other hand, a delay in cleaning and thinning does not appear as critical for the more shade-tolerant Douglas-fir, subalpine fir, and spruce. Even though the treatment areas that had not been scarified but had competing vegetation removed had the best overall vigor and growth after 25 years, it is possible that, had stand density been reduced, the early height growth advantage of larch on scarified areas might have been maintained.

Several conclusions are drawn from the study:

1. Seed-tree cutting in the western larch type generally leaves interspersed areas of scarified soil and undisturbed forest floor, on which regeneration of mixed species generally ranges from adequate to overstocked.

2. For all species in general, slashing of residual understory trees and shrubs results in greater height growth. The greatest height growth occurs in the slashed-unscarified areas where both effects of stand density and understory vegetation are minimized.

3. Larch is dominant or codominant in early stand development, particularly on scarified areas. Douglas-fir is codominant with larch in early stand development where no scarification occurs.

4. After 25 years, good-vigor larch and lodgepole pine were able to maintain significantly faster height growth on all treatments than the other major species; all vigor classes of larch grew significantly faster in diameter than Douglas-fir, except on the unslashed-unscarified treatment.

5. Although considerable flexibility is possible in the seed-tree system in guiding initial species composition, density of regeneration, and early growth through scarification and understory vegetation control, the best opportunity for long-lasting influence on composition and growth of the stand is through early cleaning and thinning operations.

6. The first 25 years is a dynamic period in the life of a stand in this forest type, and it is then that managers have the greatest opportunity to shape the character of the future forest in terms of density, composition, structure, and timber yield.

REFERENCES

Daubenmire, R.; Daubenmire, Jean B. Forest vegetation of eastern Washington and northern Idaho. Technical Bulletin 60. Pullman, WA: Washington Agricultural Experiment Station; 1968. 104 p.

Pfister, R. D.; Kovalchik, D. B.; Arno, S. F.; Presby, R. C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 174 p.

Polk, R. Brooks; Boe, Kenneth N. Succession of trees in cutover larch—Douglas-fir stands in western Montana. Montana Academy of Science Proceedings. 10: 31-37; 1951.

Roe, Arthur L. Cutting practices in Montana larch-Douglas-fir. Northwest Science. 29: 23-34; 1955.

Schmidt, Wyman C. Seedbed treatments influence seedling development in western larch forests. Research Note INT-93. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1969. 7 p.

Schmidt, Wyman C.; Shearer, Raymond C.; Roe, Arthur L. Ecology and silviculture of western larch forests. Technical Bulletin 1520. Washington, DC: U.S. Department of Agriculture, Forest Service; 1976. 96 p.

Society of American Foresters. Forest cover types of the United States and Canada. Eyre, F. H., ed. Washington, DC; 1980. 148 p.

*U.S. GOVERNMENT PRINTING OFFICE: 1986-0-676-039/41,000

Cole, Dennis M.; Schmidt, Wyman C. Site treatments influence development of a young mixed-species western larch stand. Research Paper INT-364. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 6 p.

Four treatments, all combinations of leaving or removing residual trees and shrubs or scarifying or not scarifying seedbeds, were evaluated for species differences in growth, vigor, and expression of dominance. Western larch was the dominant species in regeneration and growth but had begun to lose some of its advantage by age 25, particularly on scarified areas where overstocking commonly occurred. Douglas-fir was less sensitive to the treatments and, although significantly slower in absolute growth than larch, began to accelerate after 15 years of age. This study confirms that early cleaning and thinning will be necessary to achieve composition, density, and performance goals.

KEYWORDS: western larch, mixed species, stand development, regeneration treatments, site preparation, vegetation control

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

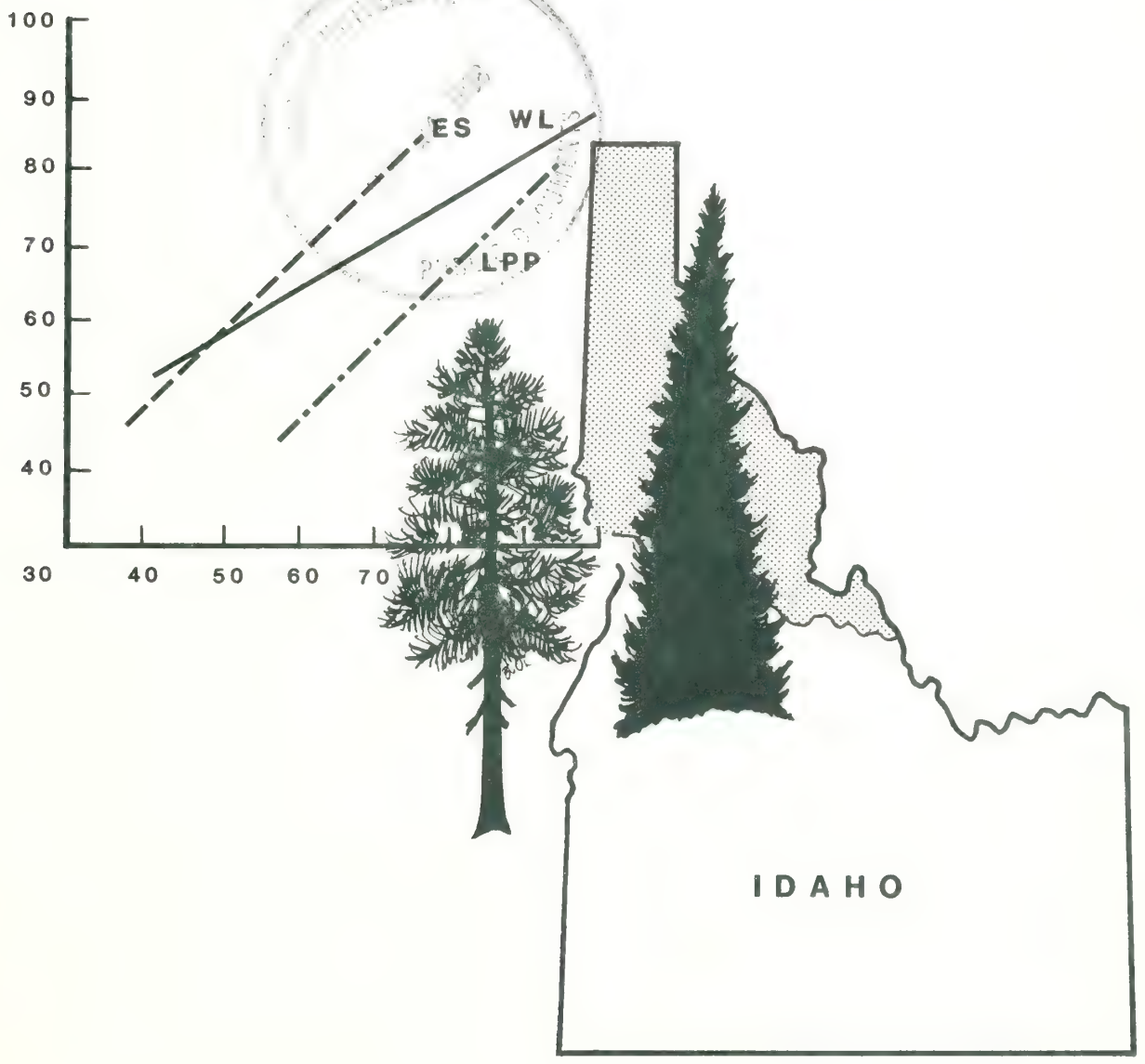
**Intermountain
Research Station**

Research Paper
INT-365

August 1986

Predicting Site Index and Height for Selected Tree Species of Northern Idaho

Brian M. Steele
Stephen V. Cooper



THE AUTHORS

BRIAN M. STEELE, a master's degree candidate in statistics at Oregon State University, shared major responsibility for the conduct of this study, particularly field sampling, data processing, and analysis. He earned a B.S. degree in biology from Cornell University. He has worked for the Intermountain Research Station as a forest technician and as a cooperator.

STEPHEN V. COOPER, research forester with the University of Montana during the study, is currently a volunteer with the Forest Service. He was a principal author of "Forest Habitat Types of Northern Idaho," from which the present study is derived. He shared responsibility for field sampling and analysis. He received B.S. (Union College, Schenectady, NY) and M.S. (State University of New York, Albany) degrees in biology, and a Ph.D. in botany (Washington State University).

ACKNOWLEDGMENTS

Major support for this study was provided by the Ecology Program of the Northern Region of the Forest Service, U.S. Department of Agriculture, through a cooperative agreement with the Intermountain Research Station.

We thank Mike Sweet (University of Montana), and Ken Neiman and Patricia Patterson (Clearwater National Forest) for providing supplementary data and field assistance.

August 1986
Intermountain Research Station
324 25th Street
Ogden, UT 84401

Predicting Site Index and Height for Selected Tree Species of Northern Idaho

Brian M. Steele
Stephen V. Cooper

INTRODUCTION

Given the manifold combinations of species, sites, and soils occurring in northern Idaho, and that growth rate, quantity, quality, and value of wood produced varies by species, foresters face complex decisions regarding species to favor on a given site. One important consideration is the relative productivity of each species. One useful estimate of productivity is site index: the height of dominant and codominant trees in a stand at an arbitrary (index) age, usually 50 years in the Western United States. Site index can be used to estimate volume growth through yield tables or as a variable in growth simulation models. Though its appropriateness has been questioned (Curtis and others 1974), the site index equation is often solved for height, which is then used as an estimate of stand height at ages other than the index age.

One method of estimating the site index of species absent from a site is the use of species on species regression equations or species comparison graphs. A number of such studies have been done in the East and Midwest (Foster 1959; Curtis and Post 1962; Carmean and Vasilevsky 1971; Carmean 1979; Carmean and Hahn 1983).

Copeland (1956) first demonstrated the utility of site index comparisons for the western white pine (*Pinus monticola*) type of northern Idaho. Deitschman and Green's (1965) study, also conducted in northern Idaho, stands as the most comprehensive of its type for the Northern Rockies. Except for western white pine, this study was done before site curves were available for most tree species in the interior West. Consequently, western white pine's site index was predicted as a function of height and age of other tree species, and environmental variables; conversely, height of the other species was predicted as a function of white pine site index, age, and environmental variables.

Our report presents equations for predicting the site index of one species from the measured site index of an associated species and equations for predicting the height of one species from its age and the measured site index of an associated species.

STUDY AREA

This study is based on data collected in the course of refining the northern Idaho habitat type classification (Cooper and others 1983). The study area extends from the Salmon River to the Canadian border, encompassing the Nezperce, Clearwater, and Idaho Panhandle National Forests, where the sampling effort was focused. The great diversity of forest environments found in this region has been described and classified by Daubenmire and Daubenmire (1968) and Cooper and others (1983).

FIELD PROCEDURES

Our methods generally followed those advocated by Pfister and Arno (1980) with respect to stand selection, sampling, and data analysis, with three important exceptions. First, stands that were not well stocked or approximately even-aged were deleted from site index analysis. Second, in order to more accurately estimate habitat type productivity (reflected by site index), our goal was to obtain height and age (at breast height, 4.5 feet) for five unsuppressed, undamaged dominant or codominant trees of each species in each stand. Third, soils were described according to Soil Survey Manual prescriptions (Soil Survey Staff 1975). We defined a stand to be a group of trees of similar age, structure, and species composition (canopy and undergrowth), occurring on an area of uniform topography, and centered on a circular 5,350-ft^2 sampling plot.

Site index values were estimated using equations or site index curves when equations were unavailable (table 1). We employed Clendenen's (1977) computer algorithm of Alexander's (1967) Engelmann spruce (*Picea engelmannii*) curves to estimate mountain hemlock (*Tsuga mertensiana*) and subalpine fir (*Abies lasiocarpa*) site indexes because site curves specific to species and region have not been developed for these two taxa. Engelmann spruce curves were chosen for extrapolation to the other two taxa because of their similarity in successional roles, undergrowth tolerance, and ecological amplitude.

In selecting site trees, no spacing or crown class limitations were imposed except that all site trees be dominant or codominant. This procedure departs from sampling procedures accompanying published site curves only in the case of western white pine. Haig's (1932) site index for white pine involved complex precriptions and the sampling of some trees that would not be considered site trees by our standards because of their inferior canopy position or low crown ratios. According to Monserud (1984a), who compared site index derived from three to four dominants to that obtained by Haig's specifications (13 to 20 trees), our western white pine site index values could be positively biased 20 percent or more.

Table 1.—Sources of curves used for computing site index[1]

Species	Estimated years to obtain breast height	Source of curve
Subalpine fir (*Abies lasiocarpa*)	([2])	Alexander (1967)
Grand fir (*Abies grandis*)	12	Stage (1959)
Western larch (*Larix occidentalis*)	5	Schmidt and others (1976)
Engelmann spruce (*Picea engelmannii*)	([2])	Alexander (1967)
Lodgepole pine (*Pinus contorta*)	7	Brickell (1970)
Western white pine (*Pinus monticola*)	5	Haig (1932)
Ponderosa pine (*Pinus ponderosa*)	5	Lynch (1958)
Douglas-fir (*Pseudotsuga menziesii*)	([2])	Monserud (1984b)
Mountain hemlock (*Tsuga mertensiana*)	([2])	Alexander (1967)

[1]All site curves based on a 50-year index age.
[2]Curves based on age at breast height were used.

Daubenmire (1961) and Lynch (1958) have warned against adding a constant number of years to breast height age to obtain total age for use with site curves requiring total age. They also indicated that the better the site, the fewer the years required to reach breast height. But, we lacked concrete data to indicate what variable number of years would be appropriate and therefore adopted the values specified by Pfister and others (1977) for western white pine, Stage (1959) for grand fir (*Abies grandis*), Schmidt and others (1976) for western larch (*Larix occidentalis*), Fiedler (1982) for lodgepole pine (*Pinus contorta*), and Daubenmire (1961) for ponderosa pine (*Pinus ponderosa*).

ANALYSIS

The data set was cleaned by discarding trees that were considerably shorter or older than the rest of the site trees in a stand. In a few cases, entire stands were rejected because of extreme variation in height or age of the site trees. First, we correlated site index between species. Scatter diagrams and least squares regressions were examined for all species combinations for which concomitant observations on six or more stands were available. A paired sample was composed of the mean site index of one species and the mean site index of an associated species. Examination of residuals indicated all associations were linear and more than 90 percent were statistically significant (95 percent confidence level).

We then grouped our data according to the number of site trees sampled in a stand. A minimum of two trees of each species per stand was generally necessary to provide sufficiently precise estimates of mean stand site indexes; a minimum of three site trees of each species further improved the regressions. Clearly, a larger number of site trees improves the reliability of the estimate of a stand's mean site index and consequently improves the predictability of the regression equations. For species combinations where enough pairs existed, regressions were restricted to stands with at least three site trees of each species per stand. The regression equations for the remaining species combinations were derived from stands with at least two site trees of each species per stand.

Second, height projection equations were computed by first considering the site index of species A and age of species B as observed values to predict the height of species B. It was assumed that the site index curves used to compute the site index of the observed species (species A) estimate site quality with negligible error. Without the assumption of measuring the age and site index with no error, the regression produces biased results.

The majority of the data was obtained from stands 45 to 120 years in age. The primary emphasis was to develop simple, flexible, empirical models for this age range, rather than biologically realistic models spanning the life span of a species. Thus, logarithmic, exponential, and second-order polynomial functions of age and site index were regressed on height. The general model form was chosen to be height predicted as a function of site index, age, and logarithmic function of age. Conformity to model assumptions was checked by examining plots of residuals versus predicted values. Coefficients of determination (R^2) and standard deviation about regression were calculated as measures of reliability; curves of estimated values generated by the regression equations were plotted over the site index curves of the dependent species to observe model behavior.

RESULTS AND DISCUSSION

Table 2 presents the site index regression equations intended for general use. Two equations are given for each species combination because the mathematics of least squares regression is such that the regression of A on B is the same as the regression of B on A only in producing equivalent coefficients of determination; the error term and the regression coefficients are almost invariably different.

Table 2.—Equations (and associated statistics) for predicting site index of a given species from the site index of associated species

List of observed species (X)	List of species (Y) whose site index is predicted	Number[1] of paired observations	Equations	Standard deviation about regression	Coefficient of determination	Site index range of observed species
				Feet	R^2	*Feet*
Douglas-fir	Engelmann spruce	22(3)	$Y = 9.56 + 0.98X$	6.62	0.67	39-76
	Grand fir	35(2)	$Y = -14.53 + 1.01X$	10.29	.56	58-94
	Lodgepole pine	41(3)	$Y = 25.00 + 0.56X$	4.15	.65	39-86
	Ponderosa pine	36(2)	$Y = 32.66 + 0.59X$	7.60	.33	50-89
	Subalpine fir	14(2)	$Y = 7.78 + 0.96X$	5.09	.84	39-78
	Western larch	50(3)	$Y = 26.06 + 0.62X$	3.49	.81	41-97
	Western white pine	24(2)	$Y = 5.01 + 0.88X$	7.46	.76	38-97
Engelmann spruce	Douglas-fir	22(3)	$Y = 14.05 + 0.69X$	5.54	.67	41-89
	Grand fir	11(2)	$Y = 0.23 + 0.70X$	9.28	.34	62-85
	Lodgepole pine	39(2)	$Y = 17.63 + 0.61X$	4.86	.76	37-89
	Mountain hemlock	16(2)	$Y = 6.32 + 0.72X$	7.93	.53	39-81
	Subalpine fir	36(2)	$Y = 2.51 + 0.93X$	6.44	.78	38-84
	Western larch	25(3)	$Y = 32.70 + 0.44X$	5.21	.46	48-84
	Western white pine	10(2)	$Y = 22.07 + 0.54X$	7.70	.56	41-90
Grand fir	Douglas-fir	35(2)	$Y = 40.73 + 0.56X$	7.66	.56	41-87
	Engelmann spruce	11(2)	$Y = 46.73 + 0.48X$	7.67	.34	33-70
	Lodgepole pine	14(2)	$Y = 43.69 + 0.38X$	7.97	.33	41-84
	Western larch	21(2)	$Y = 45.77 + 0.42X$	5.66	.51	39-84
	Western white pine	7(2)	$Y = 10.39 + 0.99X$	8.90	.34	55-71
Lodgepole pine	Douglas-fir	41(3)	$Y = -7.24 + 1.16X$	5.99	.65	44-77
	Engelmann spruce	39(2)	$Y = -6.09 + 1.24X$	6.91	.76	37-76
	Grand fir	14(2)	$Y = 1.29 + 0.88X$	12.14	.33	56-86
	Mountain hemlock	15(2)	$Y = -6.10 + 0.98X$	4.31	.77	37-59
	Ponderosa pine	9(3)	$Y = 17.45 + 0.81X$	4.23	.34	53-67
	Subalpine fir	26(2)	$Y = -18.72 + 1.42X$	7.56	.78	37-77
	Western larch	34(3)	$Y = -12.13 + 1.28X$	4.76	.74	48-76
	Western white pine	16(2)	$Y = -42.43 + 1.81X$	8.46	.69	44-68
Mountain hemlock	Engelmann spruce	16(2)	$Y = 21.06 + 0.75X$	8.11	53	25-66
	Lodgepole pine	15(2)	$Y = 15.92 + 0.78X$	3.85	.77	26-54
	Subalpine fir	24(2)	$Y = 8.88 + 0.93X$	5.66	73	26-66
	Western larch	8(2)	$Y = 15.20 + 0.89X$	7.74	42	36-56
Ponderosa pine	Douglas-fir	36(2)	$Y = 27.62 + 0.56X$	7.45	.33	53-91
	Lodgepole pine	9(3)	$Y = 31.77 + 0.42X$	3.06	34	58-72
Subalpine fir	Douglas-fir	14(2)	$Y = 2.92 + 0.88X$	4.89	.84	49-88
	Engelmann spruce	36(2)	$Y = 11.54 + 0.84X$	6.13	.78	36-87
	Lodgepole pine	26(2)	$Y = 21.84 + 0.55X$	4.72	.78	34-88
	Mountain hemlock	24(2)	$Y = 4.53 + 0.78X$	5.20	73	28-75
	Western larch	14(2)	$Y = 22.88 + 0.63X$	6.27	.64	45-88
	Western white pine	7(2)	$Y = 11.51 + 0.78X$	9.20	.59	49-82
Western larch	Douglas-fir	50(3)	$Y = -21.07 + 1.31X$	5.09	.81	47-87
	Engelmann spruce	25(3)	$Y = 3.73 + 1.05X$	8.04	.46	42-75
	Grand fir	21(2)	$Y = -27.20 + 1.21X$	9.58	.51	58-89
	Lodgepole pine	34(3)	$Y = 22.64 + 0.58X$	3.18	.74	42-82
	Mountain hemlock	8(2)	$Y = 20.47 + 0.47X$	5.64	42	42-69
	Subalpine fir	14(2)	$Y = 1.55 + 1.01X$	7.92	.64	42-85
	Western white pine	27(2)	$Y = -15.09 + 1.19X$	7.12	.74	47-86
Western white pine	Douglas-fir	24(2)	$Y = 12.12 + 0.86X$	7.38	.76	38-95
	Engelmann spruce	10(2)	$Y = 8.85 + 1.03X$	10.62	.56	41-77
	Grand fir	7(2)	$Y = 40.34 + 0.34X$	5.24	.34	56-84
	Lodgepole pine	16(2)	$Y = 34.26 + 0.38X$	3.87	.69	40-91
	Subalpine fir	7(2)	$Y = 18.72 + 0.76X$	9.02	.59	41-81
	Western larch	27(2)	$Y = 27.28 + 0.62X$	5.16	.74	38-97

[1]Minimum number of trees of both species per stand in parentheses.

Table 3 presents height projection equations for general use. The natural logarithm transformation of age was found to be the nonlinear transformation most consistently producing low standard errors from the regression equation and large explained variances. In addition, when residuals were examined, no curvilinear trends were detected, and the error components appeared to have equal variances over the range of the data. The behavior of equations with natural logarithm terms displayed a gradual decrease in height growth over time, whereas other transformations were occasionally erratic.

Some species comparisons that produced site index regression equations were not used in height projection regressions because sample size was inadequate or the range in ages was limited. These equations have been omitted.

Comparative Study Results

Despite this study's attempt to encompass a broader range of environments and a more extensive geographical area than have previous studies of this nature, our results (tables 2 and 3) are nonetheless comparable to those of the preceding studies. Deitschman and Green's (1965) regression equations predicting western white pine site index from environmental variables, heights, and ages of associated species explained 37 to 50 percent of the variation in site index, with standard deviation about regression ranging from 9.7 to 12.0 feet. For western white pine, our results (table 2) for these statistical measures were, respectively, 34 to 76 percent and 7.1 to 9.2 feet. Their regression equations predicting tree heights for other species from western white pine site

Table 3.—Projecting age-specific height for a given species from the site index of associated species

List of observed species (X)	List of species (Y) whose height is predicted	Number of paired observations	Equations[1]	Standard deviation about regression	Coefficient of determination	Age range of predicted species	Site index range of observed species
				Feet	R^2	*Years*	*Feet*
Douglas-fir	Engelmann spruce	22	$Y = -295.68 + 1.43X - 0.12A + 70.54Ln(A)$	7.49	0.89	50-156	39-76
	Grand fir	35	$Y = -114.41 + 1.10X + 0.61A + 22.31Ln(A)$	12.71	.71	40-127	59-100
	Lodgepole pine	41	$Y = -287.69 + 1.02X - 0.32A + 77.13Ln(A)$	5.65	.82	47-143	39-86
	Ponderosa pine	36	$Y = -252.34 + 0.81X - 0.37A + 74.44Ln(A)$	8.66	.69	42-200	51-90
	Western larch	50	$Y = -268.95 + 0.91X - 0.25A + 74.75Ln(A)$	5.72	.89	40-155	41-100
	Western white pine	24	$Y = -447.29 + 1.18X - 0.84A + 124.29Ln(A)$	8.34	.88	44-110	39-98
	Subalpine fir	14	$Y = -178.87 + 1.25X + 0.14A + 40.47Ln(A)$	6.33	.89	39-145	39-78
Engelmann spruce	Douglas-fir	22	$Y = -173.81 + 0.94X + 0.03A + 44.50Ln(A)$	5.92	.93	45-162	41-90
	Grand fir	11	$Y = -58.32 + 1.08X + 0.56A + 7.76Ln(A)$	7.00	.93	44-127	50-85
	Lodgepole pine	39	$Y = -153.92 + 0.99X - 0.02A + 39.83Ln(A)$	7.12	.82	52-144	38-90
	Mountain hemlock	16	$Y = -164.30 + 0.92X + 0.01A + 40.47Ln(A)$	11.24	.82	41-163	39-81
	Subalpine fir	36	$Y = -229.69 + 1.02X - 0.30A + 62.18Ln(A)$	7.23	.85	40-145	39-85
	Western larch	25	$Y = -136.81 + 0.77X + 0.01A + 40.04Ln(A)$	6.80	.91	40-163	48-90
Grand fir	Douglas-fir	35	$Y = -298.76 + 0.63X - 0.37A + 90.08Ln(A)$	9.29	.77	44-159	41-107
	Engelmann spruce	11	$Y = -180.93 + 0.72X + 0.02A + 53.88Ln(A)$	11.13	.79	47-145	33-70
	Western larch	21	$Y = -116.80 + 0.49X + 0.01A + 43.15Ln(A)$	8.06	.74	50-167	39-84
Lodgepole pine	Douglas-fir	41	$Y = -232.14 + 1.30X - 0.17A + 58.50Ln(A)$	6.63	.84	44-144	45-78
	Engelmann spruce	39	$Y = -294.86 + 1.33X - 0.43A + 77.86Ln(A)$	8.14	.86	44-200	38-78
	Mountain hemlock	15	$Y = -147.85 + 1.02X - 0.02A + 35.91Ln(A)$	5.20	.85	41-130	38-61
	Subalpine fir	26	$Y = -106.02 + 1.30X + 0.14A + 22.24Ln(A)$	7.99	.74	39-145	38-78
	Western larch	34	$Y = -296.44 + 1.64X - 0.36A + 73.48Ln(A)$	7.09	.81	53-147	49-78
	Western white pine	16	$Y = -149.83 + 1.82X + 0.14A + 28.51Ln(A)$	6.16	.82	44-135	45-69
Mountain hemlock	Engelmann spruce	16	$Y = -238.78 + 1.03X - 0.34A + 67.93Ln(A)$	11.44	.83	44-146	26-67
	Lodgepole pine	15	$Y = -192.92 + 1.12X - 0.29A + 54.90Ln(A)$	6.16	.75	51-144	38-61
	Subalpine fir	24	$Y = -207.57 + 1.14X - 0.26A + 56.77Ln(A)$	7.15	.85	43-155	26-67
Ponderosa pine	Douglas-fir	36	$Y = -122.57 + 0.81X + 0.05A + 35.18Ln(A)$	8.27	.70	48-178	38-92
Subalpine fir	Engelmann spruce	36	$Y = -209.79 + 1.03X - 0.08A + 54.31Ln(A)$	8.03	.88	44-152	28-87
	Lodgepole pine	26	$Y = -233.38 + 0.82X - 0.34A + 66.77Ln(A)$	7.22	.75	51-147	28-87
	Mountain hemlock	24	$Y = -148.02 + 1.01X + 0.12A - 33.76Ln(A)$	6.99	.87	41-147	28-74
Western larch	Douglas-fir	50	$Y = -331.12 + 1.47X - 0.32A + 80.77Ln(A)$	6.09	.89	44-162	47-90
	Engelmann spruce	25	$Y = -460.10 + 1.05X - 0.82A + 127.25Ln(A)$	8.69	.90	44-162	43-75
	Grand fir	21	$Y = -413.43 + 1.12X - 0.81A + 116.53Ln(A)$	11.68	.65	40-107	58-90
	Lodgepole pine	34	$Y = -174.42 + 0.84X - 0.07A + 48.90Ln(A)$	4.84	.86	54-143	43-83
	Western white pine	27	$Y = -281.61 + 1.79X - 0.06A + 61.78Ln(A)$	7.55	.92	44-146	47-86
Western white pine	Douglas-fir	24	$Y = -495.87 + 1.18X - 0.84A + 133.79Ln(A)$	10.66	.77	45-145	39-97
	Western larch	27	$Y = -571.46 + 1.17X - 1.03A + 155.76Ln(A)$	6.41	.92	46-165	39-97

[1]X is the mean stand site index of the observed species. A is the age of the species whose height is being protected; Ln(A) is the natural logarithm of A.

index, age, transformations of age and site index, and environmental variables explained 87 to 99 percent of the variation in tree height, with standard deviation about regression ranging from 3.4 to 8.2 feet. We are able to explain 77 to 92 percent of the variance in height of other species (table 3) from white pine site index and the age of the predicted species without employing environmental variables as additional predictors; standard deviation about regression ranged from 6.4 to 10.7 feet.

Wiant and Porter (1966) used simple linear regression to predict site index of Douglas-fir (*Pseudotsuga menziesii*), redwood (*Sequoia sempervirens*), and associated hardwoods from site indexes of other tree species in northern California. They used eight to 33 plots per regression and obtained explained variances from 13 to 55 percent. Carmean (1979), Carmean and Hahn (1983), and Carmean and Vasilevsky (1971) compared site indexes in several areas of the Midwest and upper Midwest and found linear relations between each species pair. Seven to 278 plots were used for the comparisons (notably larger than our sample size range), with one to five trees of each species on a plot. Their equations explained 40 to 91 percent of the variation in site index; standard deviation from the regression line ranged from 2.5 to 11.3 feet. Our results (table 2) show explained variances ranging from a low of 33 percent (Douglas-fir/ponderosa pine comparison) to a high of 84 percent (Douglas-fir/subalpine fir comparison); deviations about regression ranged from 3.1 feet (predicted lodgepole pine site index from western larch) to 12.1 feet (predicted grand fir site index from lodgepole pine).

Using Regression Models

The site index regression models are displayed in figures 1 through 9. The independent variable (the site index of the species used to predict) is plotted on the X-axis versus the dependent variable (the predicted site index of the specific species) on the Y-axis. For instance, to use figure 1, obtain a mean site index for Douglas-fir, say 60. Locate this value on the X-axis and read up to the western larch line and then directly across to the Y-axis, the predicted western larch site index being 63. The user is warned not to extrapolate beyond the range of the independent variable (as denoted by the length of the line) because these are empirically derived equations. Extrapolation beyond the range of the data may lead to gross errors of over- or underestimation.

The direct comparison of site index of one species to that of another must consider their respective index ages, whether it is age at breast height, or total age. Curves based on breast height age, in essence, regard the site tree to be 0 years old at the time it reaches breast height, whereas curves based on total age assume the tree to be some fixed number of years old by the time it reaches breast height. Thus, the site index of two different species that are 50 years old at breast height and of equal height will not be equal if the number of years added to reach breast height is not equal. Table 1 shows the number of years added to breast height age to obtain total age for those curves requiring total age. A further consideration when comparing tree heights at ages other than the index age is the shape of the site index curves. None of the curves employed in this study are identical; these curves reflect species-specific growth patterns. Consequently, when comparing species at ages other than 50, different heights may be registered for trees that are of equal height at the index age. The magnitude of these differences may be appreciable at older ages.

Use of Site Index Graphs

Examination of site index comparison graphs (figs. 1 through 9) reveals that the relationship of one species site index to that of its associates may change differentially in response to site quality, even when a 1:1 correspondence is observed over part of the range of site index. For example, Douglas-fir responds strongly to differences in site quality; the increase in its height growth rate from poor to good sites is comparatively greater than that exhibited by some of its associates. This observation is reflected in the steeper slopes of the Douglas-fir regression lines (compare figs. 2, 3, 7, 8, and 9). Western white pine also demonstrates a similar sensitivity to site quality (figs. 1, 4, and 8). Engelmann

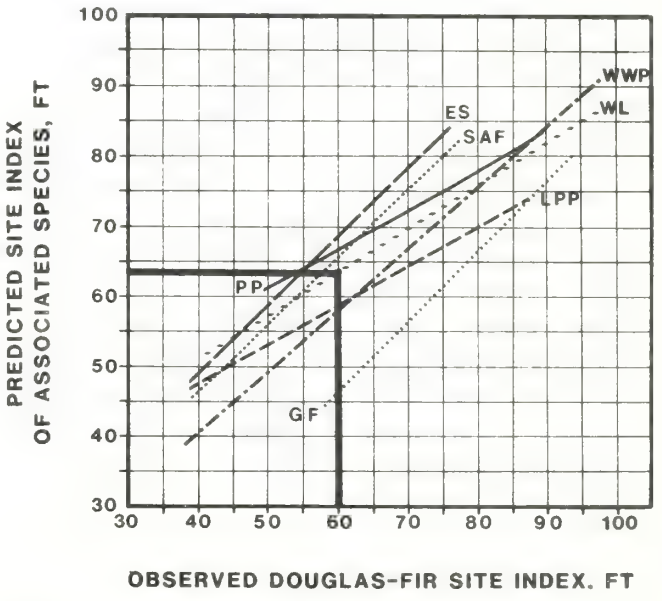


Figure 1.—Using Douglas-fir site index (x-axis) to predict that of associated species (y-axis). The diagrammed example case shows an observed Douglas-fir site index of 60 predicts a western larch site index of 63. In this and all following figures the species abbreviations are: ES, Engelmann spruce; GF, grand fir; DF, Douglas-fir; PP, ponderosa pine; WL, western larch; SAF, subalpine fir; LPP, lodgepole pine; WWP, western white pine; MH, mountain hemlock.

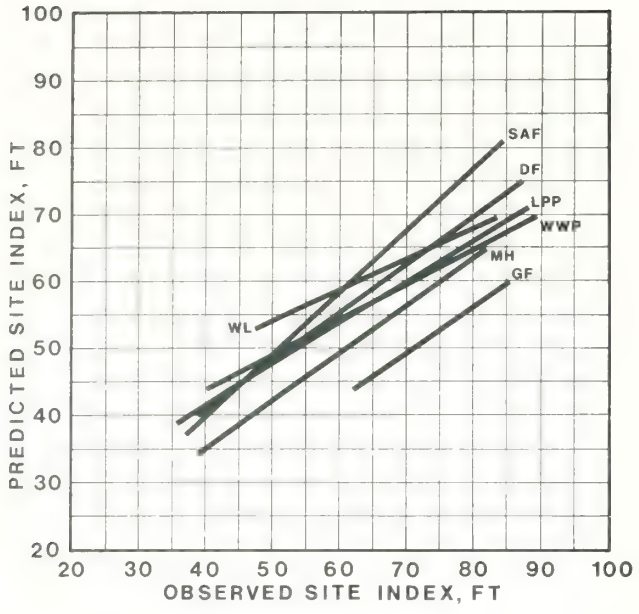


Figure 2.—Using Engelmann spruce site index (x-axis) to predict that of associated species (y-axis).

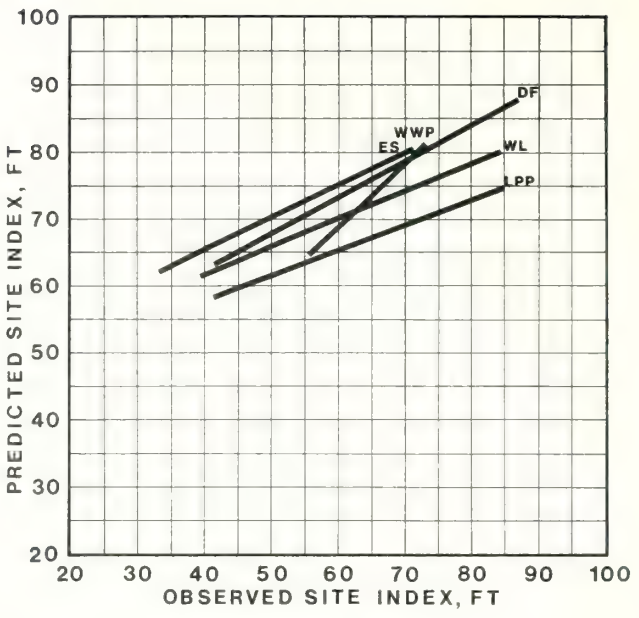


Figure 3.—Using grand fir site index (x-axis) to predict that of associated species (y-axis).

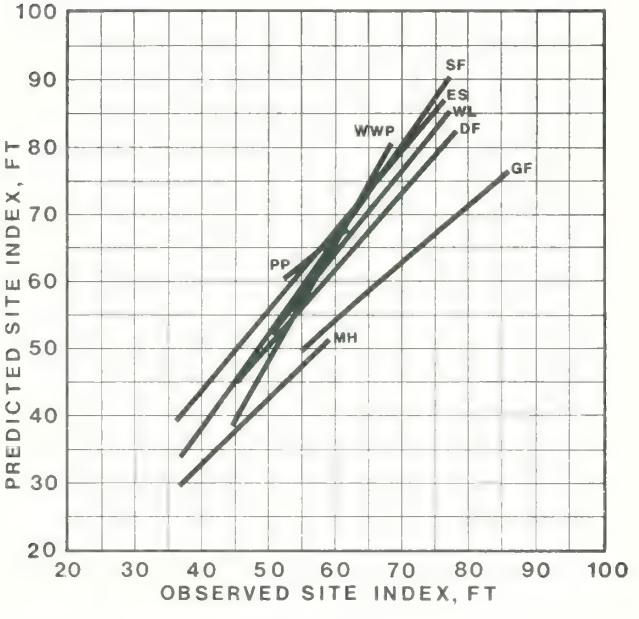


Figure 4.—Using lodgepole pine site index (x-axis) to predict that of associated species (y-axis).

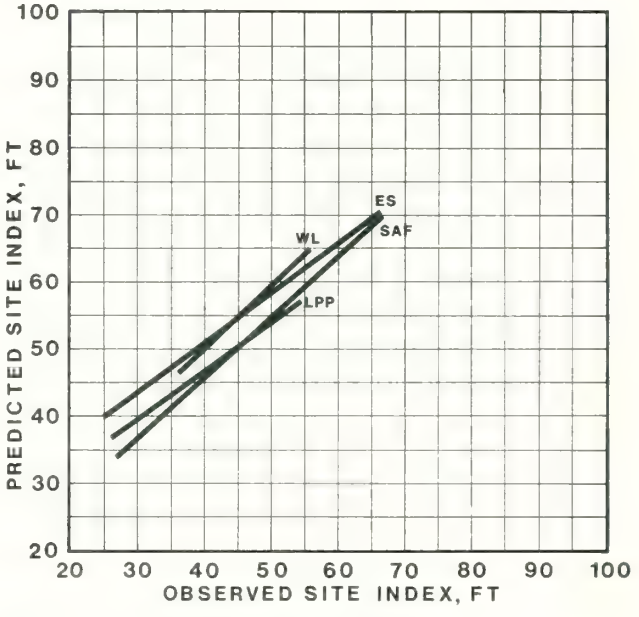


Figure 5.—Using mountain hemlock site index (x-axis) to predict that of subalpine fir (y-axis).

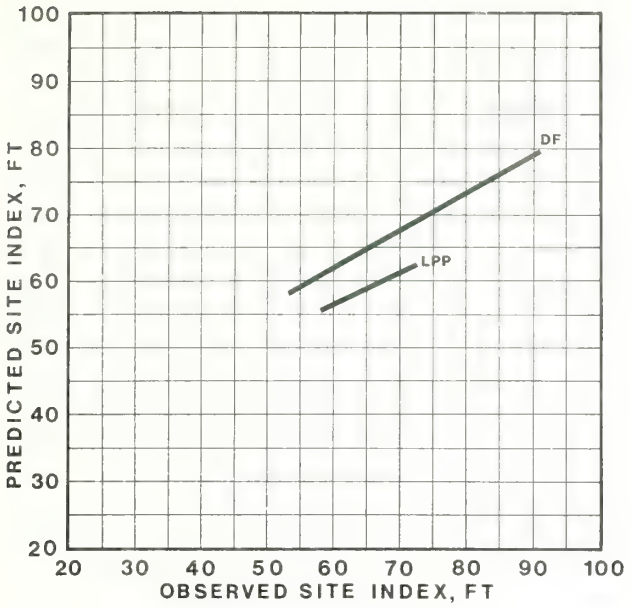


Figure 6.—Using ponderosa pine site index (x-axis) to predict that of associated species (y-axis).

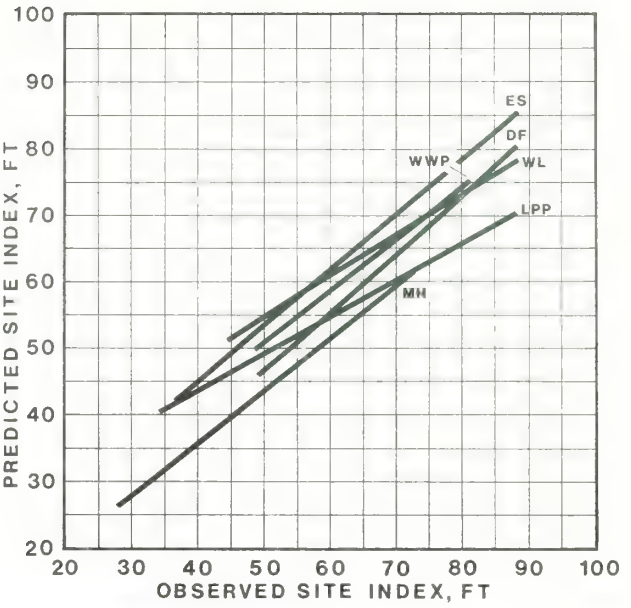


Figure 7.—Using subalpine fir site index (x-axis) to predict that of associated species (y-axis).

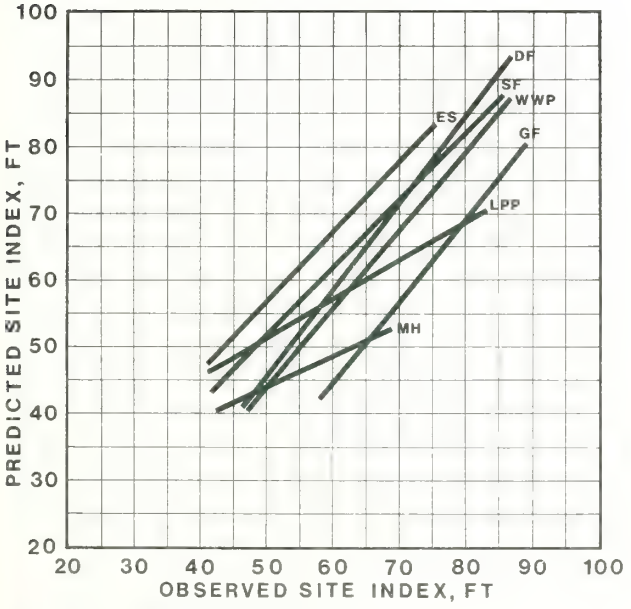


Figure 8.—Using western larch site index (x-axis) to predict that of associated species (y-axis).

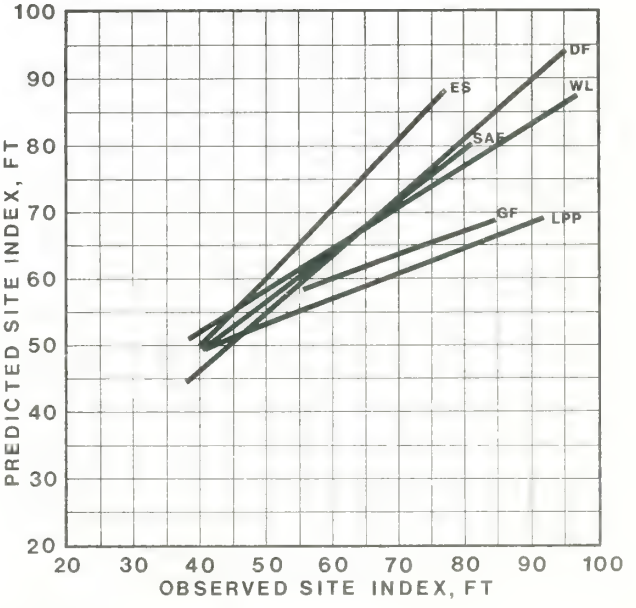


Figure 9.—Using western white pine site index (x-axis) to predict that of associated species (y-axis).

spruce and subalpine fir height growth responds strongly to site quality, although both species are capable of growing on poor-quality sites (cold, high-elevation sites) (figs. 1, 2, and 9). Western larch is somewhat less sensitive to site quality (figs. 1, 2, 7, and 9) and able to grow on all but the coldest subalpine sites, the dry portion of the Douglas-fir series, and the entire ponderosa pine series. Lodgepole pine is less sensitive yet (figs. 1, 3, 7, 8, and 9). The grand fir regression lines demonstrate unexplained erratic behavior. But figures 1 and 8 (Douglas-fir and western larch, for which large samples exist) show grand fir quite responsive to site quality. Overall, Engelmann spruce generally has the highest observed site index (figs. 1, 3, 4, 7, 8, and 9), a result attributed as much to its site index being computed on breast height age as to its superior height growth. With the exception of mountain hemlock, grand fir and lodgepole pine show the lowest observed site indexes (figs. 1, 7, 8, and 9). These observations do not reflect on height potential at any age other than index age; in fact, grand fir is often the tallest species on moderate sites.

Use of height projection equations (table 3) is limited to the recorded age range of the species to be predicted and the observed site index range of the predictor species. The equations are empirically derived from these specific ranges; do not extrapolate equations beyond the given ranges because their behavior may not correspond to expected height growth patterns.

Figures 10 through 18 portray height growth potentials of associated species, using table 3 equations to project height growth for each of the predicted species associated with a single observed species. For example, figure 12 corresponds to a stand in which the observed grand fir site index is 60; projected heights for Douglas-fir, Engelmann spruce, and western larch are graphed over only the observed age range of each species. The following site quality terms, which have been arbitrarily defined in respect to northern Idaho sites and applied to all species, are employed here only to facilitate the ensuing discussion: low, site indices <55; medium, site indices ≥ 55 but <70; high, site indices ≥ 70.

Figures 10 and 17 show that grand fir and western white pine have the greatest height growth potential on medium and better sites. Their heights are generally 5 to 10 feet taller than those of Douglas-fir, western larch, and Engelmann spruce over the age range 40 to 110 years. Douglas-fir, western larch, and Engelmann spruce are similar in height potential, with western larch somewhat taller at ages less than 70 years (figs. 11 and 12). Engelmann spruce is taller on high sites (fig. 10), whereas western larch is comparatively taller on medium sites (fig. 13). All three species demonstrate good height growth on medium to high sites.

Lodgepole pine is shown to be as tall as or taller than associated species at young ages on poor sites (figs. 15 and 16), but not nearly as tall on medium and better sites (figs. 11 and 17). Ponderosa pine also shows rapid early growth, followed by a more rapid deceleration of height growth than its associates (fig. 10). If height were the sole determinant of rotation age, then ponderosa pine apparently lends itself to short rotation management on warm, dry sites. Lodgepole pine may be similarly managed on cold and/or dry sites.

Subalpine fir has height growth comparable to associated species at younger ages, but its height is less after 70 years (figs. 11 and 12). Mountain hemlock height growth is consistently slower than all other species (figs. 11, 13, and 15).

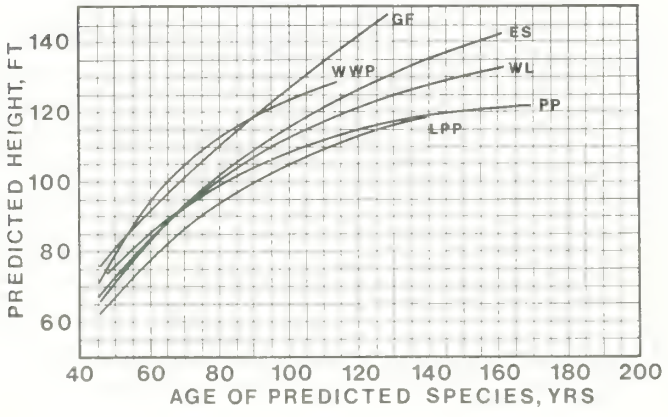


Figure 10.—Douglas-fir at site index 70 is used to project the heights of Engelmann spruce, grand fir, lodgepole pine, ponderosa pine, western larch, and western white pine; heights of the associated species (predicted variables) are projected over their sampled age ranges.

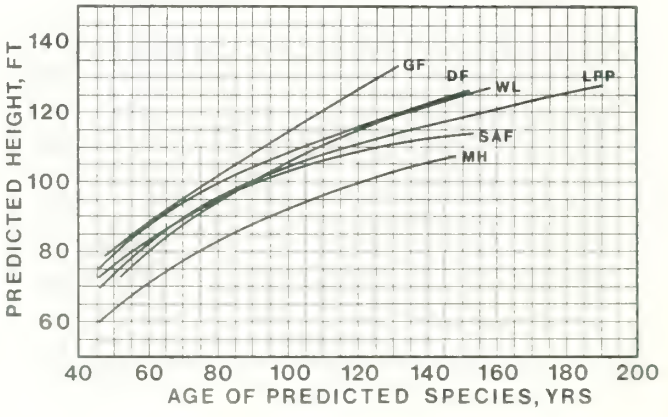


Figure 11.—Engelmann spruce at site index 70 is used to project the heights of Douglas-fir, grand fir, lodgepole pine, mountain hemlock, subalpine fir, and western larch; heights of the associated species are projected over their sampled age ranges.

Model Validation

The validity of our height growth models is most legitimately ascertained by comparing them to height growth models developed by stem analysis procedures. Monserud's (1984b) Douglas-fir height growth model developed for virtually the same geographic area as our study qualifies as the most appropriate one for comparison; we assume that Monserud's height growth curves represent the true Douglas-fir growth pattern against which our height projection curves will be compared. Figure 19a shows the height growth pattern predicted by Monserud's (1984b) equations for three site index values, 40, 60, 80 (poor, medium, and high quality sites); for these Douglas-fir site index values we have used corresponding western larch site index values (derived from table 2) and Douglas-fir age (table 3) to predict Douglas-fir height. From ages 50 to 160 years (the stipulated age range of equation applicability) the degree of correspondence between the curves appears high. Our equation overestimates Douglas-fir height by an average of 4.0 feet at site index 80 and underestimates by 1.5 feet at site index 60 and 2.4 feet at site index 40. As age increases beyond 150 years, our model produces underestimates of increasing magnitude for all site index values. Figure 19b compares Monserud's (1984b) curves

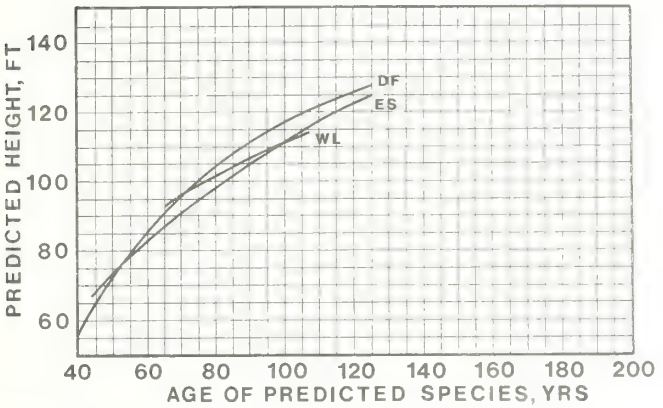


Figure 12.—Grand fir at site index 60 is used to project the heights of Douglas-fir, Engelmann spruce, and western larch; heights of the associated species are projected over their sampled age ranges.

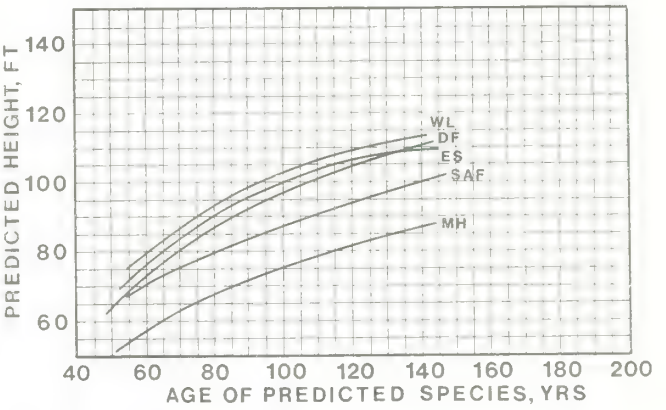


Figure 13.—Lodgepole pine at site index 60 is used to project the heights of Douglas-fir, Engelmann spruce, mountain hemlock, subalpine fir, and western larch; heights of the associated species are projected over their sampled age ranges.

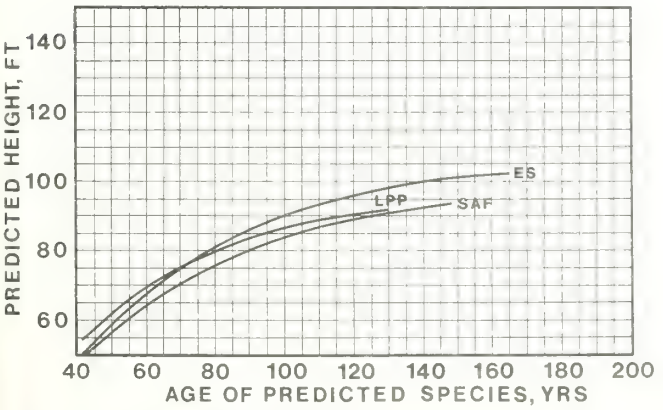


Figure 14.—Mountain hemlock at site index 50 is used to project the heights of Engelmann spruce, lodgepole pine, and subalpine fir; heights of the associated species are projected over their sampled age ranges.

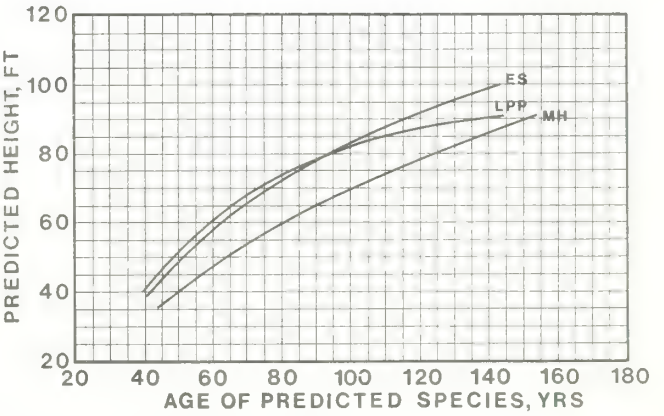


Figure 15.—Subalpine fir at site index 50 is used to project the heights of Engelmann spruce, lodgepole pine, and mountain hemlock; heights of the associated species are projected over their sampled age ranges.

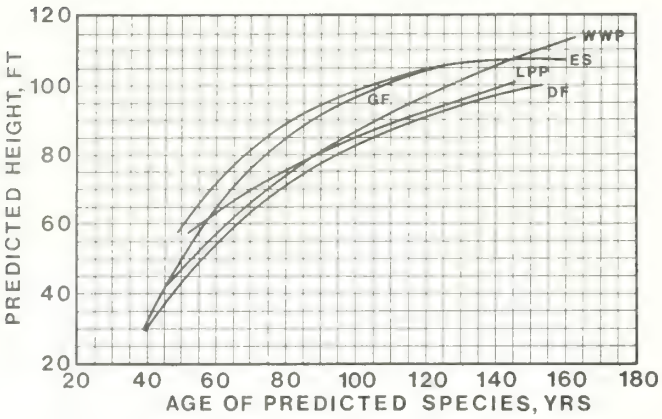


Figure 16.—Western larch at site index 50 is used to project the heights of Douglas-fir, Engelmann spruce, grand fir, lodgepole pine, and western white pine; heights of the associated species are projected over their sampled age ranges.

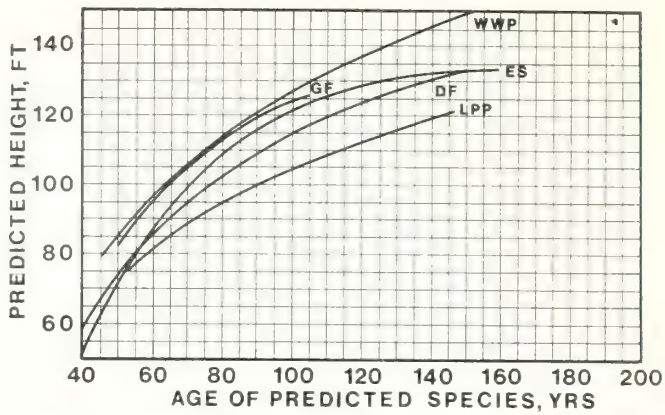


Figure 17.—Western larch at site index 70 is used to project the heights of Douglas-fir, Engelmann spruce, grand fir, lodgepole pine, and western white pine; heights of the associated species are projected over their sampled age ranges.

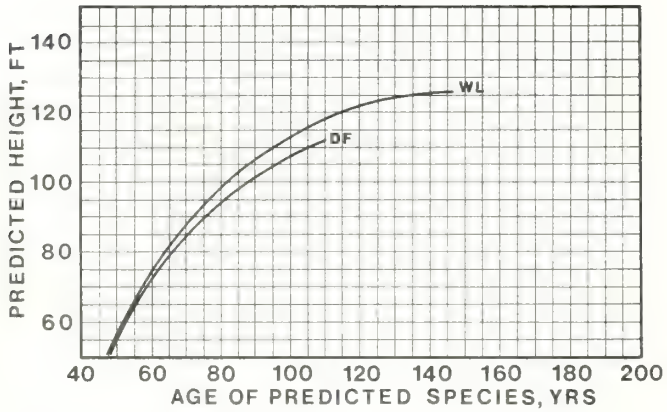


Figure 18.—Western white pine is used to project the heights of Douglas-fir and western larch; heights of the associated species are projected over their sampled age ranges.

with our projection of Douglas-fir height growth generated from observed Engelmann spruce site index. Despite the better statistics for Engelmann spruce than for western larch equations (table 3), comparison of figures 19a to 19b shows Engelmann spruce site index values to be poorer predictors of Douglas-fir height growth. There is a greater discrepancy between the predicted Douglas-fir height growth curve and the "actual" Douglas-fir height growth curve of Monserud when using Engelmann spruce as a predictor than when using western larch.

Site index and height projection comparisons are useful tools in choosing the best species for a site. Other factors such as stocking, timber value, optimum rotation age, susceptibilty to insect attack, and disease resistance must also be considered. For instance, although western white pine and grand fir are generally projected to be the fastest growing species on a given site, the land manager may favor the relatively slower growing Douglas-fir or western larch because of the susceptiblity of western white pine to blister rust and the lower timber value and higher disease risk of grand fir.

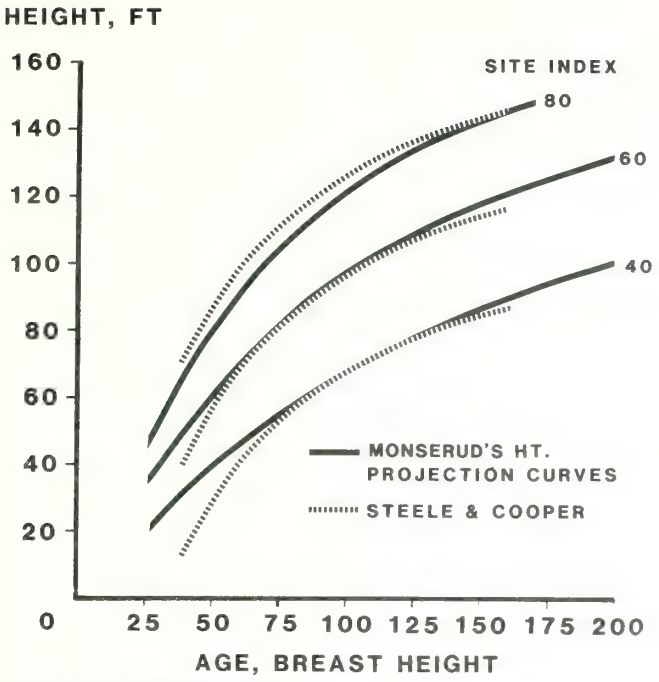


Figure 19a.—Comparison of Monserud's (1984) curves projecting Douglas-fir height growth to those generated from western larch site index and Douglas-fir age, employing authors' equations (table 3).

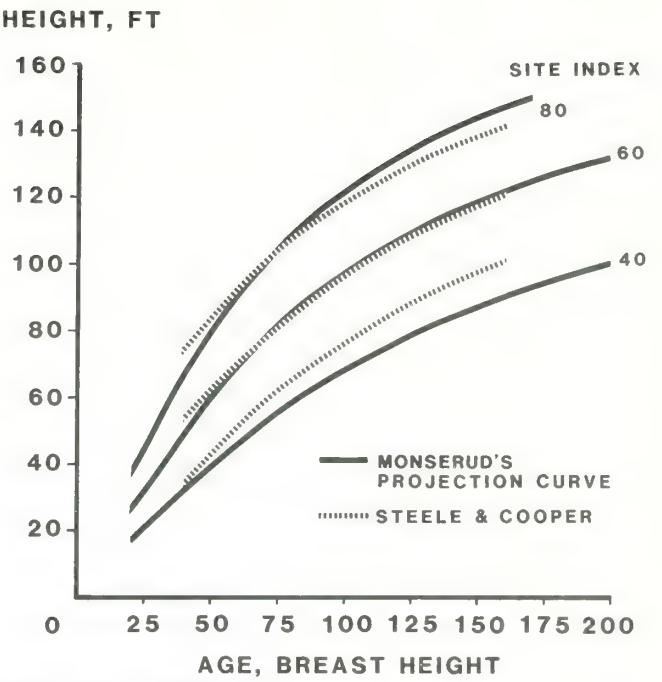


Figure 19b.—Comparison of Monserud's (1984) curves projecting Douglas-fir height growth to those generated from Engelmann spruce site index and Douglas-fir age, employing authors' equations (table 3).

SUMMARY OF METHOD TO PREDICT SITE INDEX AND HEIGHT

To predict the stand site index or height of a species from associated species, the following methodology should be followed. Select all sample trees from a stand uniform in overstory species composition, age structure, habitat type, and topography. Even-aged stands (no more than a 20-year range in the age of the dominant and codominant trees) (Alexander 1967) are preferred. Uneven-aged stands may be sampled, avoiding or rejecting trees that have suffered past suppression. Select two to five site trees of the predictor species (used to predict site index of the desired species). Site trees should be dominant or codominant, undamaged (no broken or forked tops, excessive sweep or crook, or disease), and unsuppressed (normal pattern of ring growth on the increment core) (Alexander 1967). Compute the site index of each site tree from the site curves presented in appendix A and average the values to arrive at a mean stand site index. Estimation of total age must be done with the values given in table 1.

Site index of an associated species can be computed from the equations in table 2 or read from the graph of the independent species (figs. 1 through 9) if the mean stand site index falls within the range of site index given for the independent variable in table 2. If more than one species is sampled and used to estimate the site index of the desired species, then a more reliable estimate can be made by averaging the site index estimates.

Height of an associated species can be predicted from the equations in table 3, provided: (1) the mean stand site index of the observed species is within the range of site index given for the predictor variable, and (2) the age at which the absent species height is to be predicted is also within the age range given for the predicted variable.

REFERENCES

Alexander, Robert R. Site indexes for lodgepole pine, with corrections for stand density. Research Paper RM-24. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1966. 7 p.

Alexander, Robert R. Site indexes for Engelmann spruce in the Central Rocky Mountains. Research Paper RM-32. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1967. 7 p.

Brickell, James E. Equations and computer subroutines for estimating site quality of eight Rocky Mountain species. Research Paper INT-75. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1970. 22 p.

Carmean, Willard H. Site index comparisons among northern hardwoods in northern Wisconsin and upper Michigan. Research Paper NC-169. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1979. 12 p.

Carmean, Willard H.; Hahn, Jerold T. Site comparisons for upland oaks and yellow-poplar in the Central States. Journal of Forestry. 81(11): 736-739; 1983.

Carmean, Willard H.; Vasilevsky, Alexander. Site-index comparisons for tree species in northern Minnesota. Research Paper NC-65. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1971. 8 p.

Clendenen, Gary W. Base-age conversion and site index equations for Engelmann spruce stands in the Central and Southern Rocky Mountains. Research Note INT-223. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 6 p.

Cooper, Stephen; Neiman, Kenneth; Steele, Robert. Forest habitat types of northern Idaho, review draft, May 1983. Missoula, MT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station and Northern Region; 1983. 210 p.

Copeland, Otis L., Jr. Preliminary soil-site studies in the western white pine type. Research Note No. 33. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1956. 4 p.

Curtis, R. O.; DeMars, D. J.; Herman, F. R. Which dependent variable in site index-height-age regressions? Forest Science. 20: 74-87; 1974.

Curtis, R. O.; Post, B. W. Comparative site indices for northern hardwoods in the Green Mountains of Vermont. Journal Series Paper No. 107. Burlington, VT: Vermont Agricultural Experiment Station; 1962. 6 p.

Daubenmire, R. Vegetative indicators of rate of height growth in ponderosa pine. Forest Science. 7: 24-34; 1961.

Daubenmire, R.; Daubenmire, J. B. Forest vegetation of eastern Washington and northern Idaho. Technical Bulletin 60. Pullman, WA: Washington Agricultural Experiment Station; 1968. 104 p.

Deitschman, Glenn H.; Green, Alan W. Relations between western white pine site index and tree height of several associated species. Research Paper INT-22. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1965. 27 p.

Fiedler, Carl E. Regeneration of clearcuts within four habitat types in western Montana. In: Baumgartner, D., ed. Site preparation and fuels management on steep terrain: Proceedings of the symposium; 1982; Spokane, WA. Pullman, WA: Washington State University, Cooperative Extension Service; 1982: 139-147.

Foster, Ralph W. Relation between site indexes of eastern white pine and red maple. Forest Science. 5: 279-291; 1959.

Haig, I. T. Second-growth yield, stand, and volume tables for the western white pine type. Technical Bulletin No. 323. Washington, DC: U.S. Department of Agriculture; 1932. 67 p.

Lynch, D. W. Effects of stocking on site measurement and yield of second-growth ponderosa pine in the Inland Empire. Research Paper INT-56. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1958. 36 p.

Monserud, R. A. Problems with site index: an opinionated review. In: Bockheim, J., ed. Forest land classification: experiences, problems, perspectives: Symposium proceedings. Madison, WI: University of Wisconsin, Cooperative Extension; [in press, paper presented 3/20/84].

Monserud, Robert A. Height growth and site index curves for inland Douglas-fir based on stem-analysis data and forest habitat type. Forest Science. 4(30): 943-965; 1984.

Pfister, R. D.; Arno, S. F. Classifying forest habitat types based on potential climax vegetation. Forest Science. 26: 52-70; 1980.

Pfister, Robert D.; Kovalchik, Bernard L.; Arno, Stephen F.; Presby, Richard C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 174 p.

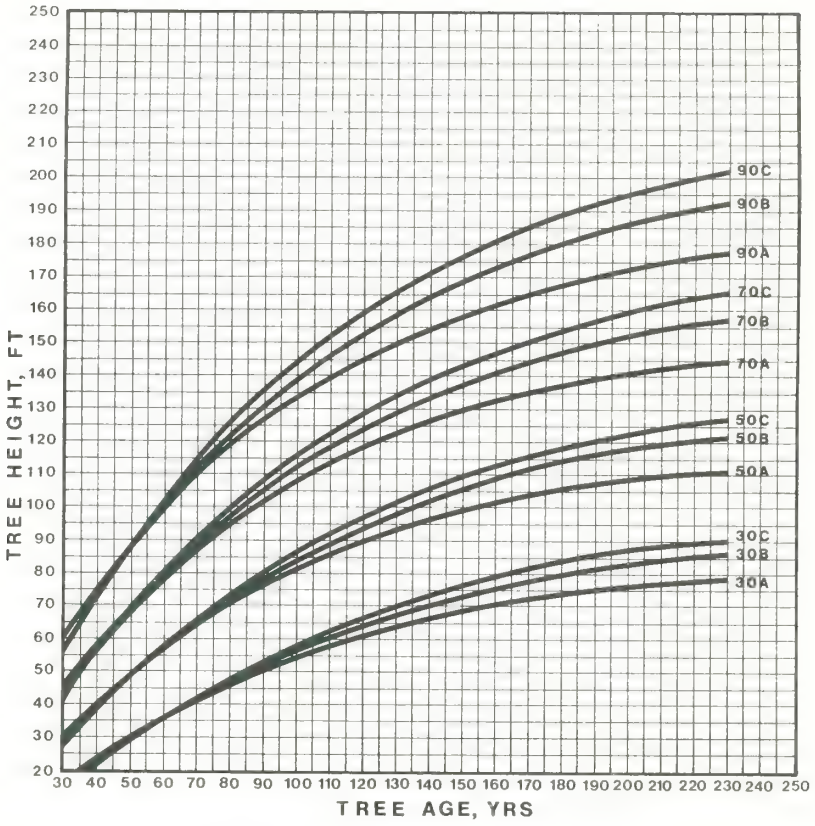
Schmidt, W. C.; Shearer, R. C.; Roe, A. L. Ecology and silviculture of western larch forests. Technical Bulletin 1520. Washington, DC: U.S. Department of Agriculture, Forest Service; 1976. 96 p.

Soil Survey Staff. Soil taxonomy. Agriculture Handbook 436. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service; 1975. 754 p.

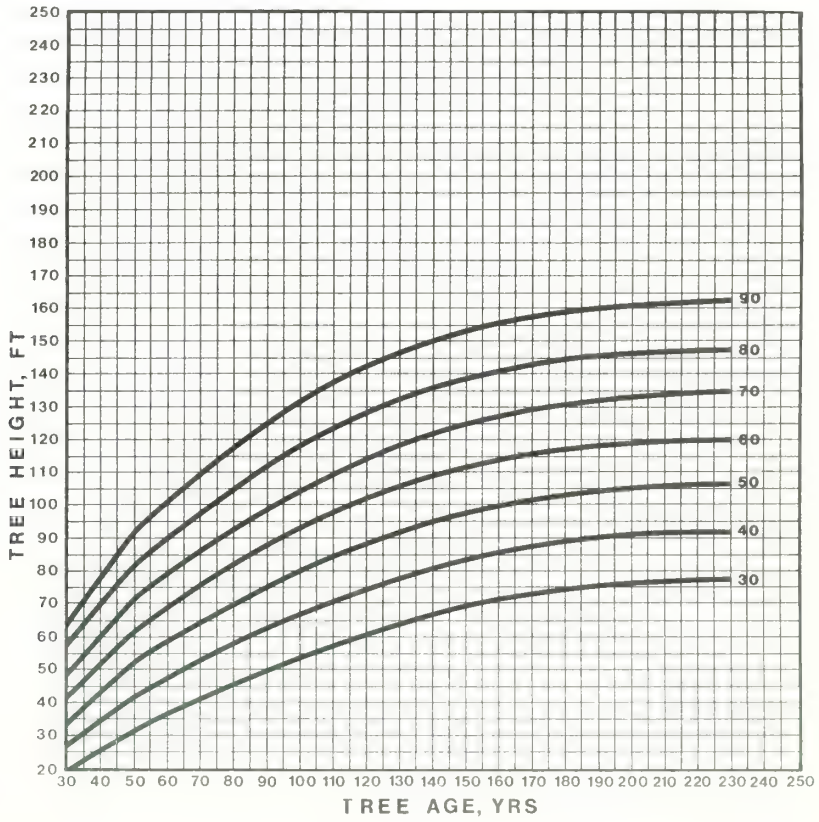
Stage, A. R. Site curves for grand fir in the Inland Empire. Research Note No. 71. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1959. 4 p.

Wiant, Harry V., Jr.; Porter, Dennis R. Site index comparisons for redwood, Douglas-fir, and some associated hardwoods. Journal of Forestry. 64: 541-543; 1966.

APPENDIX A. SITE INDEX CURVES FOR COMMON NORTHERN IDAHO TREE SPECIES, ARRANGED ALPHABETICALLY BY COMMON NAME BEGINNING WITH DOUGLAS-FIR

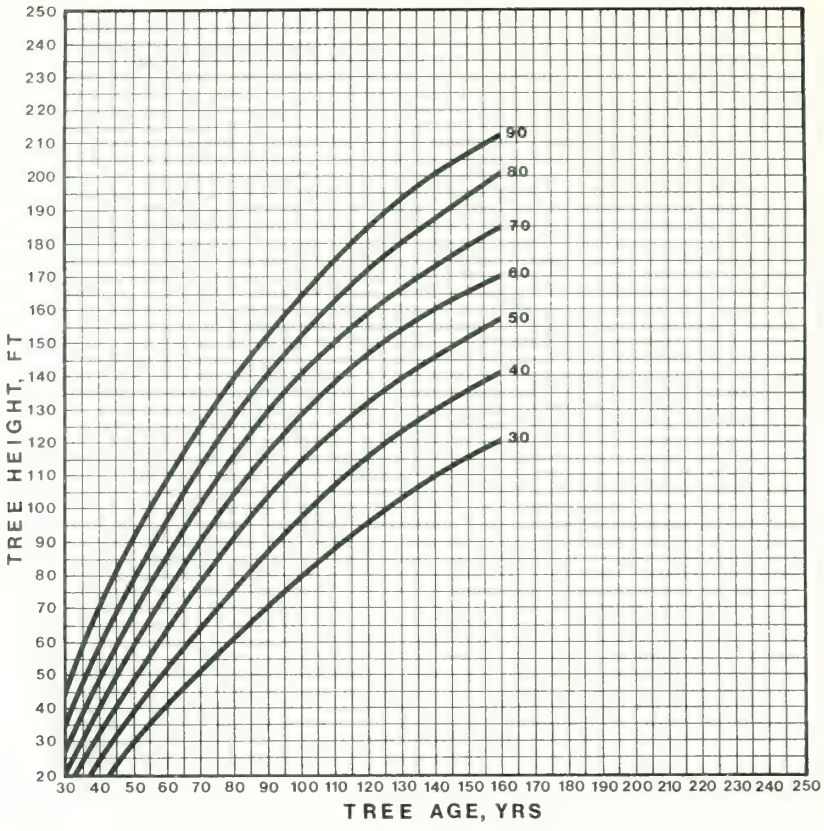


Douglas-fir. Monserud's (1984) site curves; index age is 50 years at breast height. Three sets of site curves are presented: (A) curves for stands in the western hemlock or subalpine fir series; (B) curves for stands in the grand fir or western redcedar (*Thuja plicata*) series, or stands for which the series is not known; (C) curves for the Douglas-fir series.

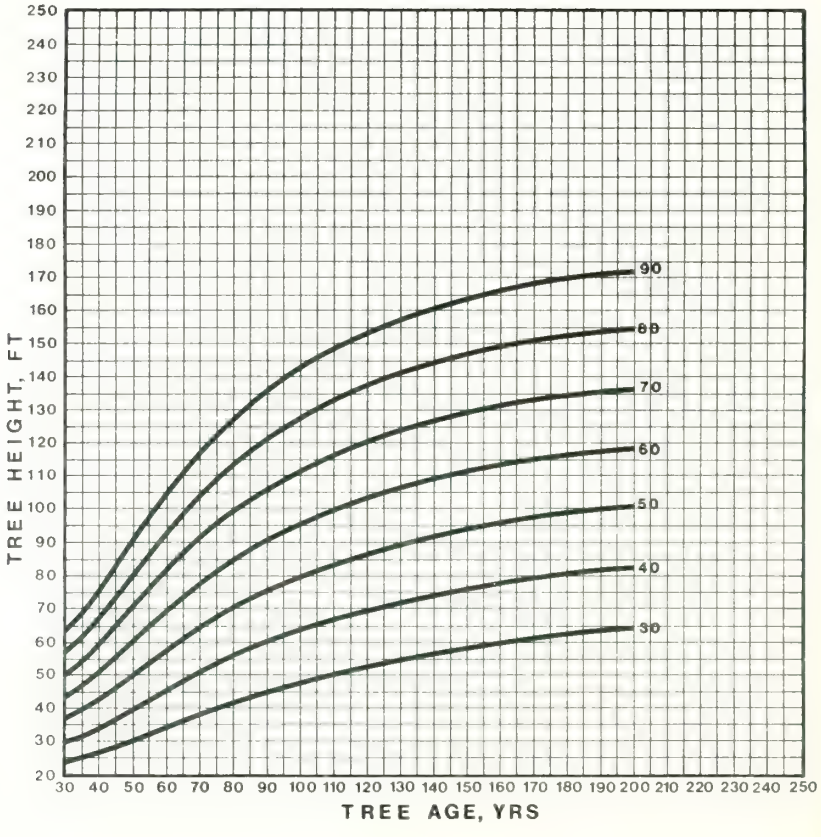


Engelmann spruce. Alexander's (1967) site curves converted to index age 50 years at breast height by Clendenen (1977).

APPENDIX A. (Con.)

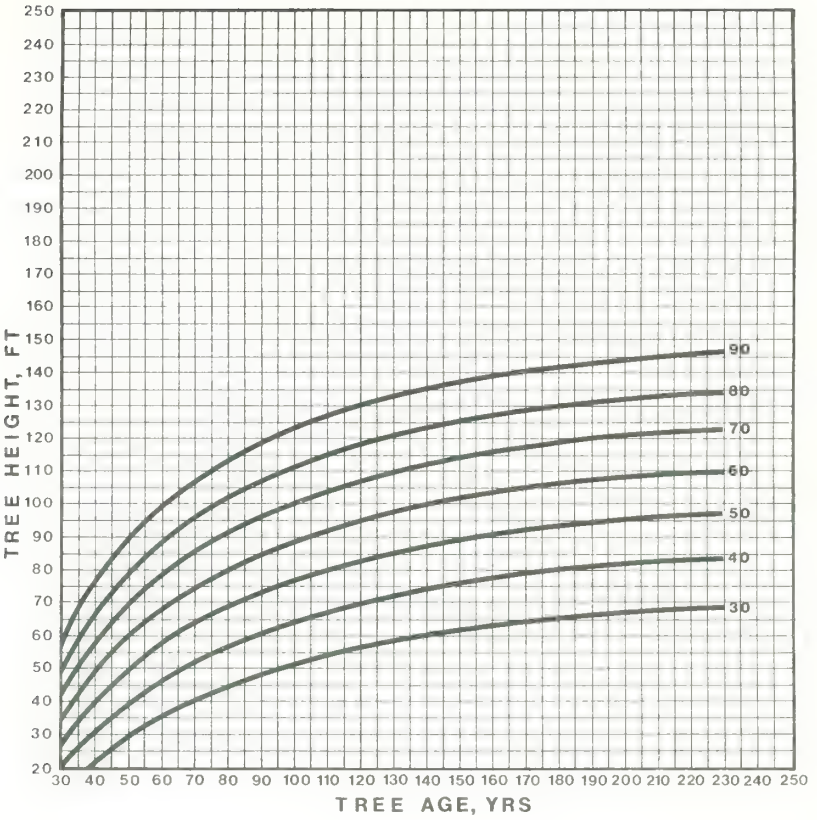


Grand fir. Stage's (1959) site curves; index age is 50 years total age (12 years added to breast height age).

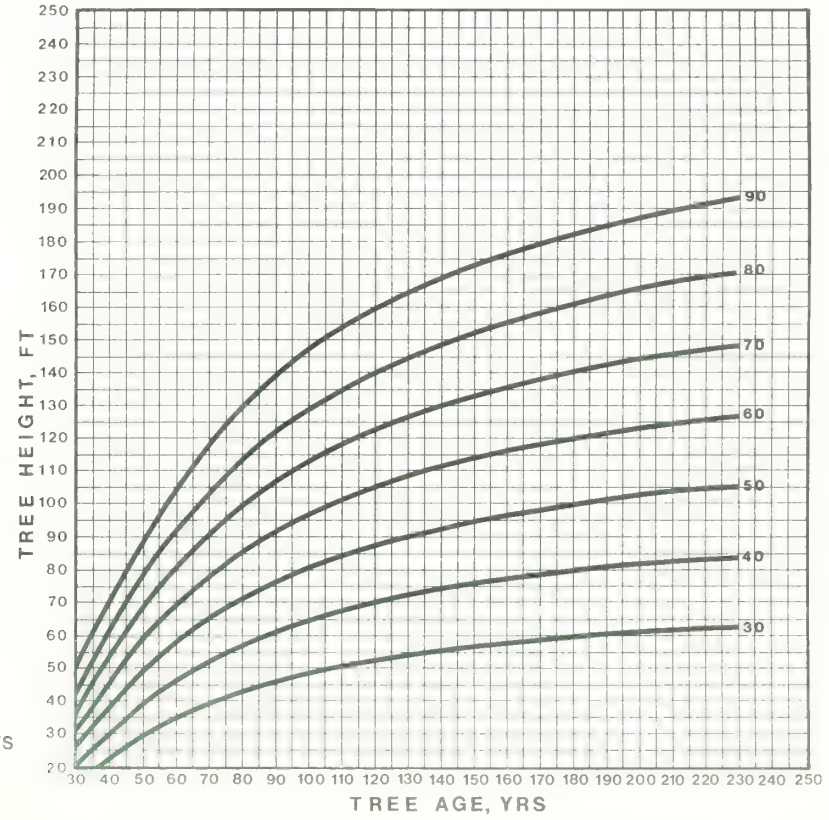


Lodgepole pine. Alexander's (1966) site curves; index age is 50 years total age (5 years added to breast height age).

APPENDIX A. (Con.)

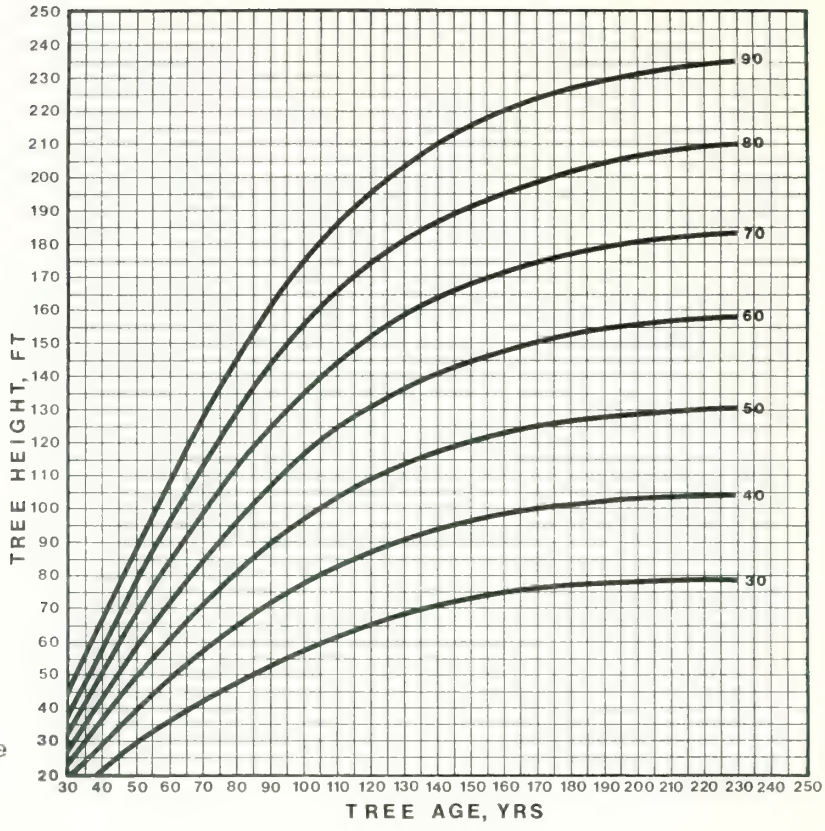


Ponderosa pine. Lynch's (1959) site curves; index age is 50 years total age (7 years added to breast height age).



Western larch. Schmidt and others' (1976) site curves; index age is 50 years total age (5 years added to breast height age).

APPENDIX A. (Con.)



Western white pine. Haig's (1932) site curves; index age is 50 years total age (5 years added to breast height age).

Steele, Brian M.; Cooper, Stephen V. Predicting site index and height for selected tree species of northern Idaho. Research Paper INT-365. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 16 p.

Forests in northern Idaho are capable of supporting as many as 10 different tree species on a given site. Comparing site indexes of species across a variety of sites is one method of assessing which species to favor in stand management. From plots across the spectrum of forest environments, site indexes (50-year index age) of species pairs (26 combinations of a possible 36 total combinations for nine species) were shown by regression analysis to be linearly related. Site index values of one species were able to explain between 33 and 85 percent of the variation in the site index of associated species. Because land managers are interested in more than comparative heights at an arbitrary index age, we developed equations for predicting the height of species A from the predictor variables, site index of associated species, and the age of species A. Graphical solutions of these equations and site index curves are provided for those without ready access to mathematical solutions.

KEYWORDS: site index predictions, height growth predictions, northern Idaho

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-366

June 1986

Large Scalps Improve Survival and Growth of Planted Conifers in Central Idaho

John P. Sloan
Russell A. Ryker

CLEMSON UNIVERSITY
AUG 29 1986
PUBLIC DOCUMENTS

THE AUTHORS

JOHN P. SLOAN is forester in the Ecology and Regeneration of Rocky Mountain Douglas-fir and Ponderosa Pine research work unit at Boise, ID. He received a B.A. degree in biology from Wartburg College and an M.S. degree in forestry from the University of Minnesota. He joined the Intermountain Station in 1984.

RUSSELL A. RYKER was project leader of the Ecology and Regeneration of Rocky Mountain Douglas-fir and Ponderosa Pine research work unit at Boise, ID. He is now retired. He received B.S. and M.S. degrees in forestry from the University of Missouri and conducted research in the silviculture of hardwoods for the North Central Forest Experiment Station prior to joining the Intermountain Research Station in 1963.

RESEARCH SUMMARY

Three conifer species were planted and compared on a large clearcut in central Idaho. Three scalp sizes were also compared. The study site is harsh and has a history of plantation failures due at least in part to a heavy coverage of elk sedge (*Carex geyeri* F. Boott).

Fifth-year results indicate that lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) had the best survival and height growth. Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) was intermediate, while Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) showed the poorest performance. On 2-ft (0.6-m) hand-made scalps, tree survival was lower and total height was less than on 4-ft (2.4-m) wide dozer strips. This was especially true for the pines.

It appears that on hot and dry sites where elk sedge or other grasses are extremely competitive, 4-ft scalps are the minimum site preparation required. Adequate site preparation along with matching of proper species to the site conditions as well as adequate control of livestock and gophers can help ensure success in reforesting these sites.

June 1986

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Large Scalps Improve Survival and Growth of Planted Conifers in Central Idaho

John P. Sloan
Russell A. Ryker

INTRODUCTION

Competition for available soil moisture between associated vegetation and young trees must always be considered when planning reforestation efforts in Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of central and southern Idaho. Elk sedge (*Carex geyeri* F. Boott), pinegrass (*Calamagrostis rubescens* Buckl.), and other grasses are especially competitive with tree seedlings because the lateral extension of their root systems allows them to exploit the same soil zones as planted trees when located as far away as 2 ft (0.61 m) or more from the tree (Loewenstein and others 1968). Of these grasses, elk sedge is the most competitive in central Idaho (Spence and Woolley 1936).

Elk sedge is a fibrous-rooted species that produces a greater number of roots and penetrates the soil to a greater depth than its grass and herb associates (Spence 1937). It is a perennial that tolerates unfavorable conditions such as high moisture stress (Sampson 1917). The root system of elk sedge is much more extensive than the aboveground foliage (fig. 1). Although the plant diagrammed in figure 1 is only 12 inches (30 cm) tall and 10 inches (26 cm) wide, the roots spread 56 inches (142 cm) and reach a depth of 75 inches (190 cm). Because of elk sedge's extensive root systems and its ability to compete for soil moisture, the spaces commonly found between sedge plants are often occupied below ground and may not be good spots to plant trees.

Elk sedge is present in most inland Douglas-fir and ponderosa pine forests. Of 49 central Idaho forest habitat types that have Douglas-fir either as a climax species or a major seral species, 44 have elk sedge in the undergrowth (Steele and others 1981). In 10 habitat types, elk sedge was found in every stand sampled. Canopy coverage of elk sedge was estimated as high as 43 percent. Moreover, because of its extensive root systems, the effective site occupancy of elk sedge was much greater.

Other grasses with root systems less extensive than elk sedge can also be excessively competitive where coverage is high. In California, Baron (1962) planted ponderosa pine seedlings for three consecutive years in plots he had sown to big bluegrass (*Poa ampla* Merr.), hard fescue (*Festuca ovina duriuscula* L.), pubescent wheatgrass (*Agropyron trichophorum* K. Richter.), redtop (*Agrostis alba* L.), orchard grass (*Dactylis glomerata* L.), perennial ryegrass (*Lolium perenne* L.), tall oatgrass (*Arrhenatherum elatius* [L.] Presl.), and timothy (*Phleum pratense* L.). Establishment of the pine seedlings became less successful each year as competition from the grasses increased. Larson and Schubert (1969) showed that for ponderosa pine, both root and top growth was greater when seedlings were grown in the absence of competition from Arizona fescue (*Festuca arizonica* Vasey) and mountain muhly (*Muhlenbergia montana* [Nutt.] Hitchc.).

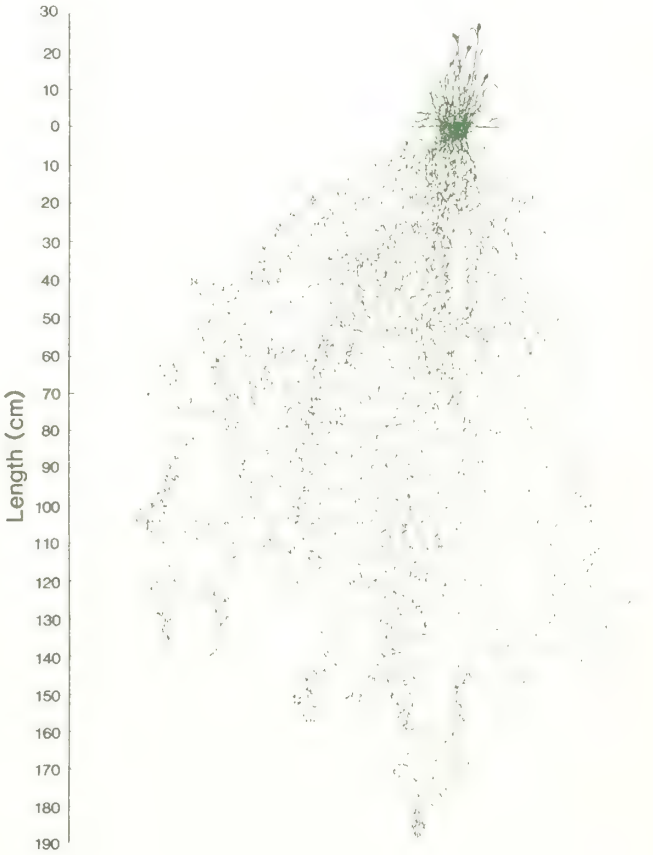


Figure 1.—Representative diagram of a fibrous root system of sedge (*Carex* sp.) from a north slope in the Boise River watershed, southwestern Idaho (Spence and Woolley 1936).

Control of competition from sedge and grass is often necessary for a successful plantation. But how large is the vegetation-free area needed by each tree to assure survival and a reasonable rate of growth?

According to Gutzwiler (1976), the primary considerations in determining the minimum effective size of cleared spots are the condition of the forest floor and the rooting characteristics of existing vegetation. When vegetation completely occupies a planting site, scalp size and depth must be increased in order to prevent competition from underlying roots. Lotan and Perry (1983) say that scalps must be a minimum of 18 inches by 18 inches (46 by 46 cm), and on droughty sites they should be larger. Stewart and Beebe (1974) found no significant increase in second-year ponderosa pine survival when they compared 2-ft (0.61-m) scalps to no site preparation in hard fescue and pinegrass on two different soils of central Washington. Heidmann (1963) tested scalp sizes on an Arizona site covered with mixed grasses consisting mainly of mountain muhly and Arizona fescue. He found that scalping as opposed to no site preparation significantly increased survival of ponderosa pine. However, survival differences between scalp sizes of 16-inch (41-cm) diameter, 26-inch (66-cm) diameter, and complete removal of all vegetation on the plot were not statistically significant.

Hall (1971) found that ponderosa pine seedling survival 5 years after planting was higher on 4-ft (1.2-m) scalps than on 2-ft or 6-ft (0.61-m or 1.8-m) scalps in central Idaho. Slit scalps 1.5 to 2 ft (0.46 to 0.61 m) long and 6 to 10 inches (15 to 25 cm) wide have sometimes been successful on pumice soils of central Washington (Stewart 1978). Loewenstein and others (1968) showed that scalping increased first-year ponderosa pine survival dramatically, but differences in survival between seedlings on scalps of 1, 3, and 5 ft (30, 91, or 152 m) were small. However, favorable moisture conditions throughout the season may have been partially responsible for the lack of significant differences. Larson and Schubert (1969) recommend that in order to establish ponderosa pine in the Southwest, grass must be killed or removed from the site before trees are planted.

Miller and Brewer (1984) found that, in northern Idaho, dozer scarification significantly reduced 3-year height growth of containerized Douglas-fir compared to no treatment where competing vegetation was light and first-year precipitation was above normal. Lotan and Perry (1983) maintain that discontinuous furrows or scarified strips are preferable because animals will use continuous strips as walkways.

This paper contains the results of a 5-year study comparing Douglas-fir, ponderosa pine, and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) survival and height growth after planting in three sizes of hand-made and machine-made scalps. Though competition may also be reduced by other means such as spot applications of herbicides, this study involved only mechanical scalping.

STUDY SITE

The study site was within a large clearcut in the Grouse Creek drainage on the Mountain Home Ranger District of the Boise National Forest. Characterized by strongly dissected faulted bench land, Grouse Creek is in the southern part of the Idaho batholith. Well-drained, gravelly sandy loam skeletal soils of granitic genesis predominate. The amount of soil moisture available to young trees depends largely on summertime precipitation. The site is approximately 6,000 ft (1 830 m) in elevation and is a *Pseudotsuga menziesii/Berberis repens* habitat type (PSME/BERE; Douglas-fir/Oregongrape) (Steele and others 1981).

The PSME/BERE habitat type occurs mainly in southeastern Idaho and adjacent Utah, and extends into southern portions of central Idaho. The elk sedge phase of this type occurs mainly in the southern batholith section in central Idaho.

This habitat type has moderate to high timber yield capability (Steele and others 1981). It occupies a variety of aspects at lower to midelevations—4,500 to 7,700 ft (1 370 to 2 350 m)—of the forested zone. Usually Douglas-fir is the only tree species that grows on these sites, but in the elk sedge phase ponderosa pine is a major seral species within its elevational range. Lodgepole pine is an associated species in some areas.

The Grouse Creek study area has gently rolling topography with slopes generally less than 30 percent. Cold air appears to drain less rapidly here than in other areas of similar elevation, and extremes in temperature may be a major hinderance in regenerating Douglas-fir, especially in a large clearcut.

Coverage of elk sedge was estimated on 10 randomly located 4-milacre plots on each aspect of the study area. Coverage ranged from 10 percent on areas greatly disturbed during logging to 65 percent on areas with minimal disturbance. The average for each aspect was between 35 and 40 percent (fig 2).

Clearcuts in the area have been heavily grazed by sheep each year since logging in the early 1960's. Douglas-fir has been planted twice on the site with little success. Seven years separate the last planting and the beginning of this study.

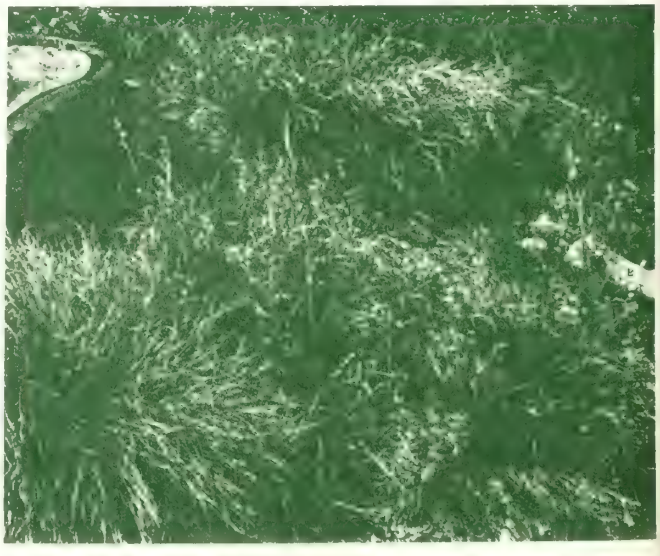


Figure 2.—Grouse Creek study site with typical ground coverage of elk sedge.

METHODS

We repeated the scalping test on three aspects (northeast, southeast, and northwest) within the study area. Test sites on the northwest and southeast sites were fenced to exclude sheep grazing. The northeast site was left unprotected in order to determine effects of sheep grazing. We used a completely randomized block experimental design with five blocks on each aspect. We conducted 3×3×3 factorial analysis of variances for surviving trees, gopher-caused mortality, and height growth (measured from the ground to the top of the terminal bud or tallest lateral if no terminal) after the fifth growing season. Where significant differences were revealed, we did multiple comparisons of means using the studentized maximum modulus (Gabriel 1978).

Each block contained three experimental units (scalping treatments); each unit was 120 ft (37 m) long. One unit consisted of a single row of 2- by 2-ft (0.61- by 0.61-m) hand scalps spaced 4 ft (1.2 m) apart from center to center. Ten trees each of Douglas-fir, ponderosa pine, and lodgepole pine were planted in the scalps. The order of the species in the first three scalps was determined randomly. The same order was repeated in each subsequent group of three scalps. A second unit contained two rows of 4- by 4-ft (1.2- by 1.2-m) scalps made by a hydraulically operated 4-ft blade mounted on the rear of a small tractor. The two rows were 8 ft (2.4 m) apart with 8 ft between scalp centers within a row. The third unit was one row of trees planted 4 ft apart down the middle of an 8-ft-wide dozer-scalped strip. The three species were planted in the 4-ft scalps and dozer strips in the same alternating pattern described above for the 2-ft scalps. Each experimental unit contained 30 planted trees, 10 of each species. All three site preparation treatments removed up to 6 inches (15 cm) of topsoil from the immediate vicinity of the planted trees.

Trees (2-0 stock) were planted in spring 1975. Roots were pruned to 12-inch (30-cm) length at Lucky Peak Nursery and relatively uniform-sized trees of each species were selected for the study. The trees were hand planted in auger holes. The initial height of each seedling was measured and recorded as well as the height at the end of each of the first five growing seasons. Mortality was determined each year and the likely cause of death recorded.

The unfenced area on the northeast aspect was lightly grazed by a herd of 2,800 sheep once during the second growing season (1976). Again in the third growing season (1977), a herd of 2,865 sheep grazed through the unprotected blocks of the study. This time the grazing was slower and heavier. Finally, the unfenced blocks were very heavily grazed for a few hours in the fifth growing season (1979) by 2,074 sheep. Visible damage to seedlings caused by sheep was recorded in 1976, the first year of grazing, and each of the subsequent 4 years. (Erosion is not expected to be a problem with any of the three treatments. The 2-ft scalps have the least potential for erosion.)

We did not use an unscalped control plot because after two plantation failures it was apparent that the site required site preparation in order to establish tree seedlings. The 2-ft scalp was accepted as the standard for comparison.

RESULTS

At the end of the first five growing seasons, we gathered data on survival and mortality and on height growth and frost damage.

Survival

The 86 percent survival rate of the lodgepole pine was significantly greater than the 73 percent survival for ponderosa pine at the 95 percent level of confidence (table 1). In turn, ponderosa pine survival was significantly greater than the 65 percent survival of Douglas-fir. Survival of all species on the 2-ft (0.61-m) scalps was 61 percent, significantly less than on 4-ft (1.2-m) scalps (80 percent) and on dozer strips (83 percent). We found no significant difference in survival between the three aspects.

The difference between survival on the 2-ft scalps and the other two site treatments has widened each year since planting (fig 3). When the three species were combined, average first-year survival ranged from 95 percent in the 2-ft scalps to 98 percent on the dozer strips. At the end of the fifth year, average survival ranged from 63 percent on the 2-ft scalps to 82 percent on the dozer strips. For nearly all nine combinations of species and site preparation, the mortality rates declined sharply during the fifth growing season.

Table 1.—Fifth year survival and mean height of surviving trees

Tree species and treatment	Survival	Height
	Pct	*cm*
Douglas-fir		
2-ft scalp	49a[1]	20.2a
4-ft scalp	69bc	21.9a
dozer strip	77bcd	24.7ab
species total	65	22.3
Ponderosa pine		
2-ft scalp	59ab	20.8a
4-ft scalp	80cd	29.6bc
dozer strip	81cd	32.0cd
species total	73	27.5
Lodgepole pine		
2-ft scalp	75bcd	26.4abc
4-ft scalp	91d	36.1de
dozer strip	92d	39.9e
species total	86	34.1

[1]Means followed by the same letter are not significantly different, $\alpha = 0.05$. Mean comparisons methods according to Gabriel (1978).

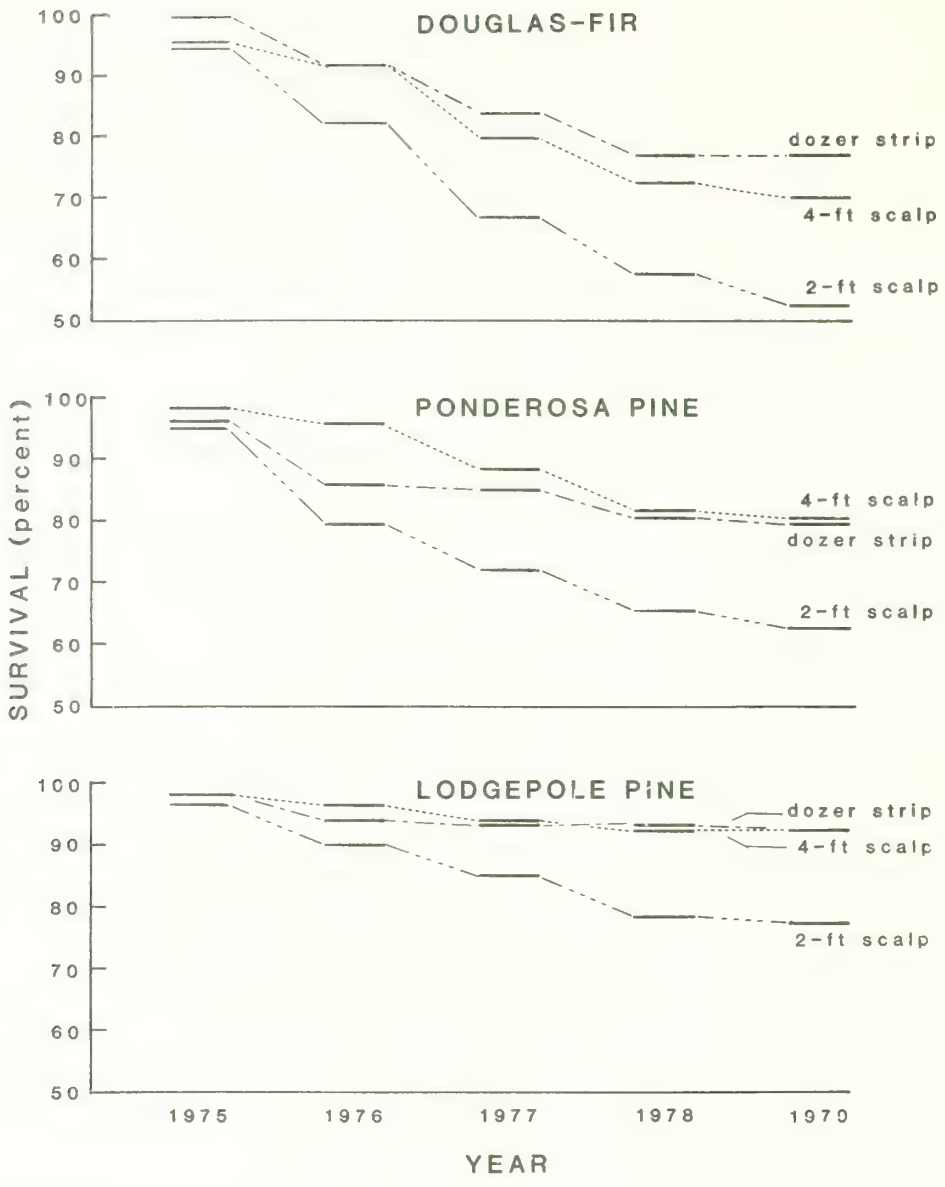


Figure 3.—Tree survival during the first 5 years after planting. The lines are averages for the three aspects.

Causes of Mortality

More than half the seedling mortality on all three aspects was not identifiable at the time of measurement. The primary cause of unidentified mortality is likely to have been moisture stress due to poor root growth after planting and gopher damage to the root system.

A 3×3×3 analysis of variance revealed significant differences in the number of seedlings killed by gophers among the different aspects and among species (tables 2 and 3). Gopher kill was significantly greater on the northwest aspect than on the northeast ($\alpha = 0.01$), with the southeast intermediate (fig. 4). Gophers killed significantly more ponderosa pine than lodgepole pine, with Douglas-fir intermediate ($\alpha = 0.05$). There was no apparent relationship between the number of trees killed by gophers and the site preparation treatment.

Because the northeast aspect was the only unfenced area, it was the only aspect where trees were killed by sheep. During the small amount of grazing, sheep killed 20 trees (19 percent of the total mortality on that site), most of which were trampled or browsed. About half the trees killed were Douglas-fir. Ponderosa pine mortality was almost as high, but only three lodgepole pine trees were killed by the sheep.

Table 2.—The average number of trees killed by gophers on each aspect during the 5-year period after planting

Aspect	Trees killed
	No.
Northwest	1.22a[1]
Southwest	0.93ab
Northeast	0.36b

[1]Values shown are means for 45 experimental units, each containing 10 trees. Means followed by the same letter are not significantly different, α = 0.01.

Table 3.—The average number of trees of each species killed by gophers during the 5-year period after planting

Aspect	Trees killed
	No.
Ponderosa pine	1.20a[1]
Douglas-fir	0.82ab
Lodgepole pine	0.49b

[1]Values shown are means for 45 experimental units, each containing 10 trees. Means followed by the same letter are not significantly different, α = 0.05.

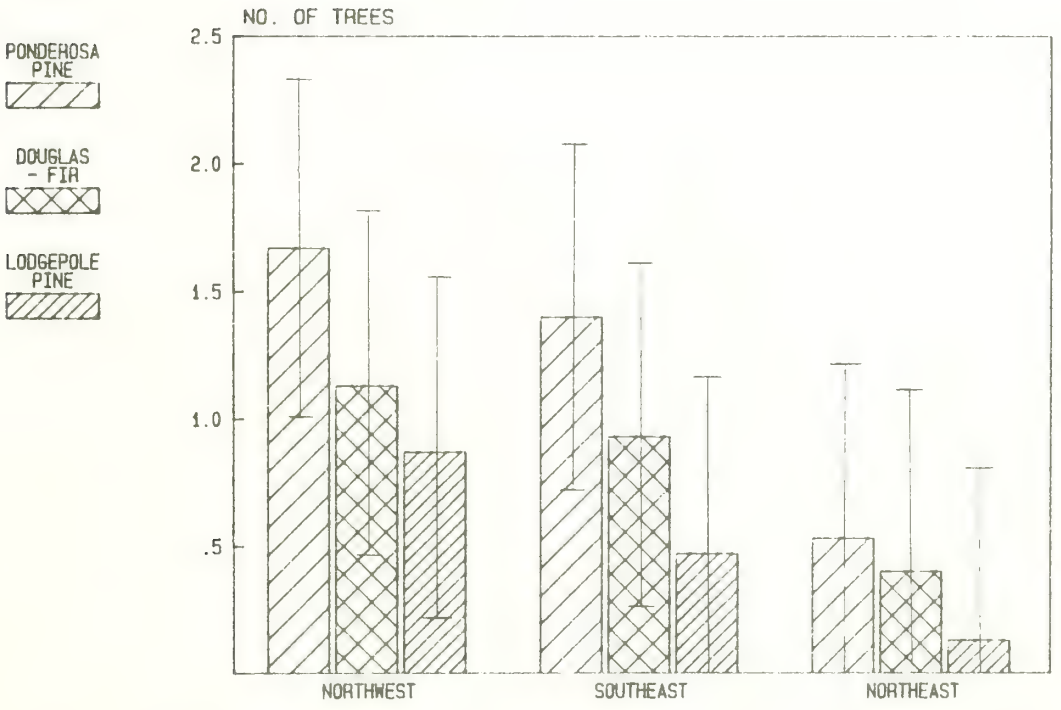


Figure 4.—Average number of trees killed by gophers. Bars depict the number killed by gophers per 10-tree plot. Lines depict mean comparison intervals by Gabriel (1978). Treatment means with lines that overlap are not significantly different.

Height Growth

Our analysis of variance for the mean total height at the end of the fifth growing season showed several significant relationships at the 95 percent level of confidence (table 1). Lodgepole pine seedlings were taller (13.4 inches or 34.1 cm) than ponderosa pine (10.8 inches or 27.5 cm), which, in turn, were taller than Douglas-fir (8.8 inches or 22.3 cm). Trees were tallest on the dozer strips (12.7 inches or 32.2 cm), and those on the 4-ft (1.2-m) scalps (11.5 inches or 29.2 cm) were taller than on the 2-ft (0.61-m) scalps (8.9 inches or 22.5 cm).

For both lodgepole and ponderosa pine the heights were significantly taller on the dozer strips and 4-ft scalps than on the 2-ft scalps (fig. 5). For Douglas-fir, the differences were not statistically significant.

The initial height of Douglas-fir averaged 5.1 inches (13 cm) with a range of 2 to 9 inches (5 to 23 cm). Ponderosa pine initial tree height averaged 3.2 inches (8 cm) and ranged from 2 to 5 inches (5 to 13 cm), while that of lodgepole pine averaged 4.7 inches (12 cm) with a range of 2 to 7 inches (5 to 18 cm). We plotted fifth-year heights over initial heights and found no apparent relationship.

At the end of the fourth growing season, the rate of terminal leader elongation was increasing faster on the dozer strips for all three species (fig. 6). The next fastest rate increase was on 4-ft scalps for the pines. The Douglas-fir rate of terminal leader elongation was similar for 4-ft and 2-ft scalps.

After five seasons, lodgepole pine averaged 55 percent taller than Douglas-fir and 25 percent taller than ponderosa pine. Figure 7 shows the Grouse Creek site and heights of several trees after 10 growing seasons.

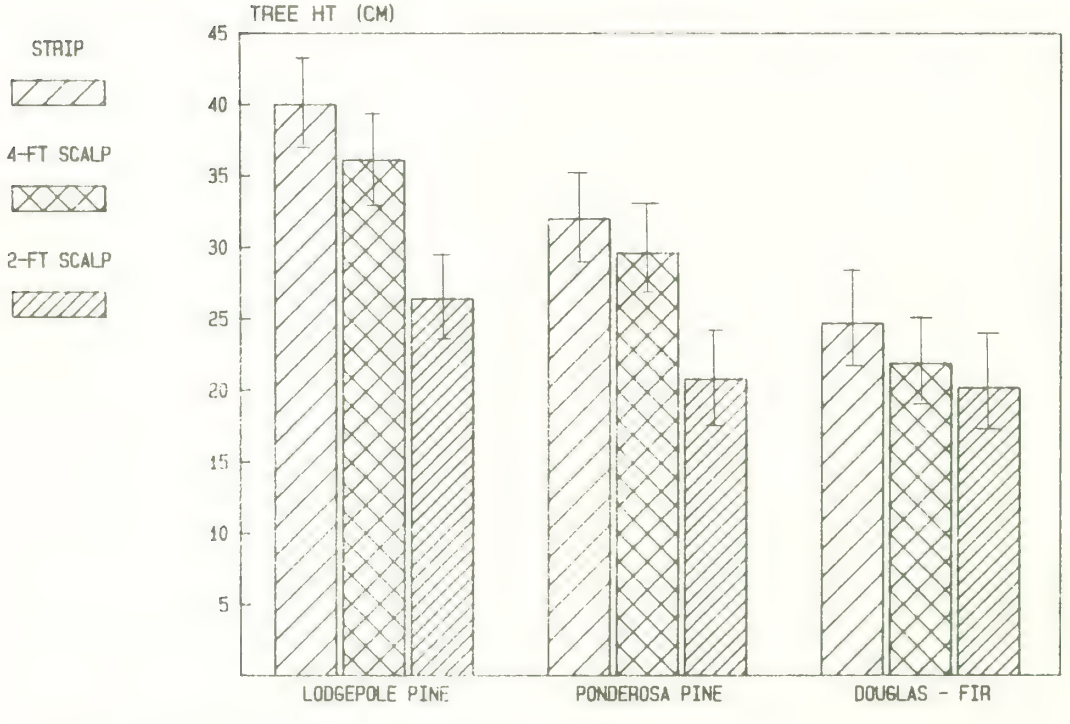


Figure 5.—Average tree heights. Bars depict tree heights in centimeters. Lines depict mean comparison by Gabriel (1978). Treatment means with lines that overlap are not significantly different.

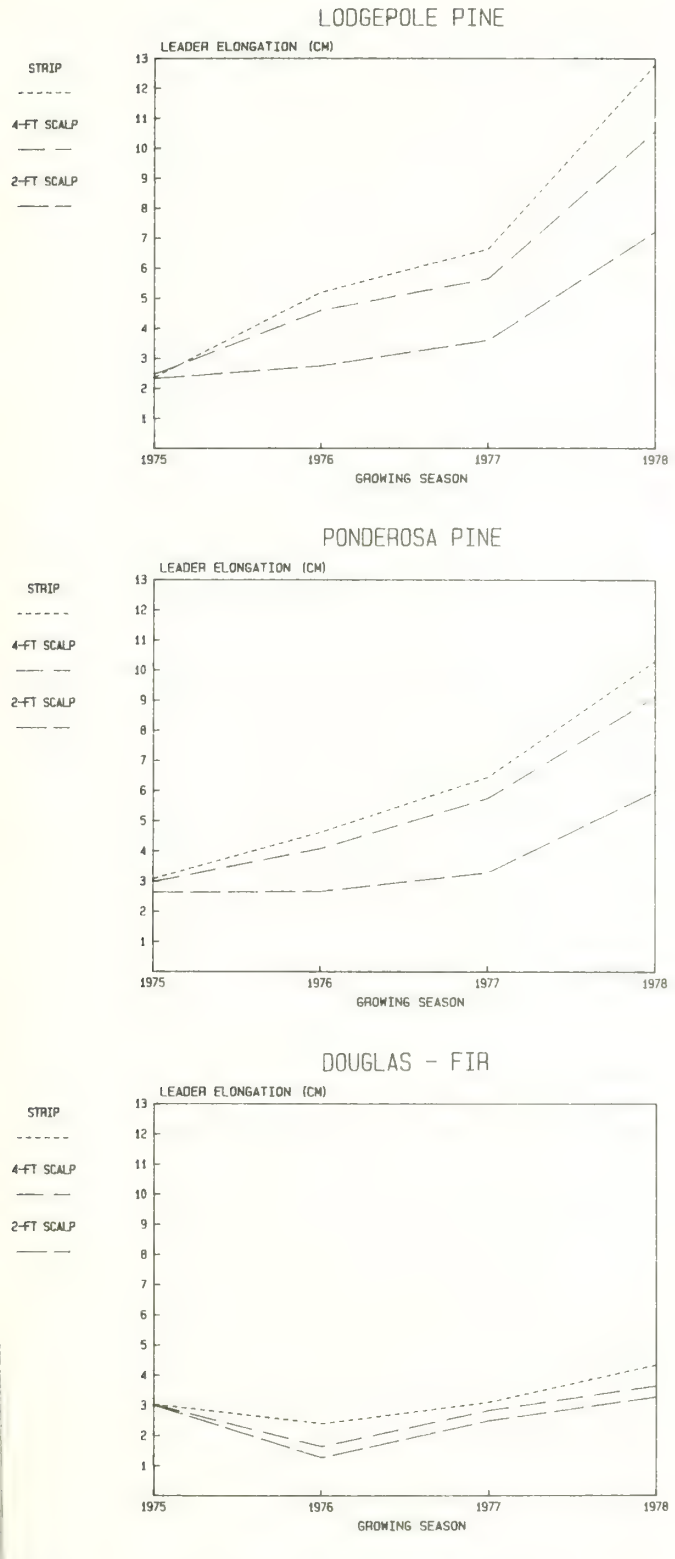


Figure 6.—Leader elongation for species and site treatments during the first four growing seasons.

Frost Damage

A severe frost in June of 1976 did not directly cause mortality in this study, but frost was credited with preventing 19 percent of the Douglas-fir seedlings from making leader growth during the second growing season. Of the Douglas-fir seedlings, 22 percent in both 2-ft and 4-ft (0.61- and 1.2-m) scalps and 14 percent in dozer strips were frost damaged severely enough to prevent leader growth. The extent of frost damage to Douglas-fir on the three aspects was similar. This frost damage may have reduced the fifth-year mean heights of Douglas-fir, but had minimal effects on the comparison of site treatments. The frost had no apparent effect on the two pine species.

Figure 7.—Grouse Creek study site in 1984 after 10 growing seasons.

DISCUSSION AND CONCLUSIONS

There is a contradiction on a site like Grouse Creek where we have potential for high timber productivity yet regeneration is so extremely difficult. This seemingly illogical situation can be explained by two factors (Running 1982): (1) the microclimate changes when a site is clearcut, and (2) physiologically, mature trees are more tolerant of temperature and moisture extremes than are young seedlings. Since clearcutting, elk sedge has expanded to use most of the available summertime moisture resource, considered to be the major limiting plant growth factor on the site. So, to allow tree seedlings a share of the moisture, the elk sedge coverage must be decreased.

Lodgepole and ponderosa pine responded more to the larger scalps than did Douglas-fir. Height growth on the 4-ft (1.2-m) scalps and dozer strips was superior to that on the 2-ft (0.61-m) scalps for both pines, but the differences in height growth for Douglas-fir were not statistically significant. At the end of the study the differences in height growth on the three site preparations were widening at an increasing rate for the pines. The growth rate for Douglas-fir on the dozer strips was increasing at a slightly faster rate than on the 4-ft and 2-ft scalps.

The chances of seedling survival were higher on the dozer strips and 4-ft scalps than on the 2-ft scalps for all three species.

Although there was no significant difference in survival between the three aspects, the causes of mortality differed widely. Gophers were responsible for 48 and 35 percent of the total mortality on the northwest and southeast aspects, respectively. The northeast aspect had only 15 percent gopher-kill. Of the mortality on the northeast aspect, 19 percent was caused by sheep grazing. From the data collected in this study we cannot explain why we got less gopher damage on the northeast aspect.

A small amount of frost damage to Douglas-fir did occur during this study, but the data were too limited to determine if any of the site preparations increased the chances of frost damage.

Because the site preparation treatments tested in this study removed up to 6 inches (15 cm) of topsoil from the immediate vicinity of the planted trees, we suspect that the increased height growth was a response to less competition for available soil moisture rather than for nutrients. We need to test a toothed scalping blade that would remove the vegetation but leave most of the topsoil on the scalped area. Another possible method would be use of herbicides to create scalps yet leave topsoil in place. We would expect greater height growth response from both methods, but the more fertile topsoil may allow a quicker invasion of scalps by vegetation.

As expected, the climax species, Douglas-fir, tended not to perform as well in the large clearcut as the two seral species, ponderosa pine and lodgepole pine. At 6,000 ft (1 830 m) ponderosa pine is nearing its upper elevational limit in that part of Idaho. Had the plantation been 500 ft (150 m) lower, ponderosa pine may have performed better. In large clearcuts of this nature, unprotected Douglas-fir seedlings are susceptible to frost damage. Where lodgepole pine is an associated species on this habitat type, large clearcuts can be most readily regenerated by planting lodgepole. Douglas-fir and ponderosa pine can also be established, but perhaps at greater costs. Regeneration of Douglas-fir on this kind of site would be more successful in small clearcuts, group selection cuts, or shelterwood cuts (Steele and others 1981; Ryker and Losensky 1983).

The 2-ft (0.61-m) hand-made scalp is too small on sites with a high coverage of elk sedge. Competition from elk sedge is not greatly reduced because the sedge roots spread well beyond the aboveground plant canopy and still occupy much of the space below a 2-ft scalp. On 2-ft scalps, tree survival was lower and total height was less than on 4-ft (1.2-m) machine-made scalps and 8-ft (2.4-m) dozer strips. This was especially true of the pines.

In deciding how big the scalps must be to insure seedling survival at a minimum cost, many factors must be considered. High temperature and plant water stress are the most common reasons for seedling mortality in the Northern Rocky Mountains (Running 1982). If vegetation is light and moisture is adequate as described by Miller and Breuer (1984), little or no site preparation may be required. It appears that on hot and dry sites a more extensive site preparation is needed. Although not as important here, competition for nutrients and light should also be considered. Scalping removes topsoil and nutrients from the seedling microsite, which may cause a reduction in initial growth on some sites. More study is needed in this area. Competition for light is important to remember on sites supporting taller grasses, forbs, and shrubs. The best we can do is match the species to the site and then give the seedlings as much help as they need at the time of planting.

Elk sedge seems to create severe competition in many central Idaho plantations. Each year of this study, survival of seedlings in the 2-ft scalps fell further behind the 4-ft scalps and strip treatments. The dramatic decline in seedling survival on 2-ft scalps, as seen especially in the first to third years, is similar to what has been observed in plantations of central Idaho.

Even though elk sedge and other grasses of central Idaho are tough competitors they can be overcome by doing an adequate job of site preparation. Matching the cutting method to the species as well as stand and site conditions, adequately preparing the site before planting, and following up with adequate control of livestock and gophers will help ensure a successful forest plantation on these sites.

REFERENCES

Baron, Frank J. Effects of different grasses on ponderosa pine seedling establishment. Research Note 199. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1962. 8 p.

Gabriel, K. Ruben. A simple method of multiple comparisons of means. Journal of the American Statistical Association. 73(364): 724-729; 1978.

Gutzwiler, Jerry R. Mechanical site preparation for tree planting in the inland northwest. In: Conference proceedings, tree planting in the Inland Northwest; 1976 February 17-19; Pullman, WA. Pullman, WA: Washington State University; 1976: 117-133.

Hall, Dale O. Ponderosa pine planting techniques, survival, and height growth in the Idaho batholith. Research Paper INT-104. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1971. 28 p.

Heidmann, L. J. Effects of rock mulch and scalping on survival of planted ponderosa pine in the southwest. Research Note RM-10. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1963. 7 p.

Larson, M. M.; Schubert, G. H. Root competition between ponderosa pine seedlings and grass. Research Paper RM-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; 1969. 12 p.

Loewenstein, H.; McConnel, L. P.; Pitkin, F. H. Root development and survival of planted ponderosa pine seedlings as influenced by competing vegetation. Station Paper No. 5. Moscow, ID: University of Idaho, Forest, Wildlife, and Range Experiment Station; 1968. 13 p.

Lotan, James E.; Perry, David A. Ecology and regeneration of lodgepole pine. Agriculture Handbook 606. Washington, DC: U.S. Department of Agriculture; 1983. 51 p.

Miller, Daniel L.; Breuer, David W. Effects of site preparation by burning and dozer scarification on seedling performance. Forestry Technical Paper TP-84. Lewiston, ID: Potlatch Corporation; 1984. 7 p.

Running, Steven W. Insolation and heat effects on tree seedlings on newly cleared sites. In: Symposium proceedings, site preparation and fuels management on steep terrain; 1982 February 15-17; Spokane, WA. Pullman, WA: Washington State University; 1982: 87-92.

Ryker, Russell A.; Losensky, Jack. Ponderosa pine and Rocky Mountain Douglas-fir. In: Burns, Russell M., tech. comp. Silvicultural systems for the major forest types of the United States. Agriculture Handbook 445. Washington, DC: U.S. Department of Agriculture, Forest Service; 1983: 53-55.

Sampson, A. W. Important range plants: their life history and forage value. Bulletin 545. Washington, DC: U.S. Department of Agriculture; 1917: 34-36.

Spence, Liter E. Root studies of important range plants of the Boise River Watershed. Journal of Forestry. 35(8): 747-754; 1937.

Spence, L. E.; Woolley, S. B. Root systems of important range plants of the Boise River Watershed. 1936. Unpublished paper on file at: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, Boise, ID.

Steele, Robert; Pfister, Robert D.; Ryker, Russell A.; Kittams, J. A. Forest habitat types of central Idaho. General Technical Report INT-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 138 p.

Stewart, Ronald E. Site preparation (Chapter 7). In: Regenerating Oregon's forests. Corvallis, OR: Oregon State University Extension Service; 1978: 99-134.

Stewart, R. E.; Beebe, T. Survival of ponderosa pine seedlings following control of competing grasses. In: Proceedings of the Western Society of Weed Science. 27: 55-58; 1974.

Sloan, John P.; Ryker, Russell A. Large scalps improve survival and growth of planted conifers in central Idaho. Research Paper INT-366. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 9 p.

Responses of three species of conifers were assessed in a large clearcut in central Idaho. Survival and height growth of Douglas-fir, lodgepole pine, and ponderosa pine for 5 years after planting were related to 2-ft and 4-ft scalps and dozer strips on a *Pseudotsuga menziesii* var. *glauca/Berberis repens* habitat type.

KEYWORDS: Douglas-fir, lodgepole pine, ponderosa pine, site preparation, plantation protection, *Carex geyeri*, *Pseudotsuga menziesii* var. *glauca/Berberis repens* h.t., central Idaho, survival, height growth

---

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-367

June 1986

Mountain Pine Beetle in Ponderosa Pine: Effects of Phloem Thickness and Egg Gallery Density

Gene D. Amman
Judith E. Pasek

CLEMSON UNIVERSITY

THE AUTHORS

GENE D. AMMAN is project leader of the Mountain Pine Beetle Population Dynamics research work unit in Ogden, UT. He joined the work unit in 1966. Prior to joining the Intermountain Station, he was research entomologist with the Southeastern Forest Experiment Station in Asheville, NC, doing biological control and ecological research on the balsam woolly aphid. He began his career with the Rocky Mountain Forest and Range Experiment Station in Fort Collins, CO, as research assistant on sampling populations and mortality factors of mountain pine beetle and spruce bark beetle. He has B.S. and M.S. degrees from Colorado State University and a Ph.D. degree from the University of Michigan.

JUDITH E. PASEK is research entomologist with the Rocky Mountain Forest and Range Experiment Station's Protection and Improvement of Trees in the Great Plains research work unit in Lincoln, NE. At the time of this study, she was biological technician on the Mountain Pine Beetle Population Dynamics research work unit in Ogden. She holds a B.S. degree from the University of Michigan, an M.S. degree from the University of Missouri, and presently is a Ph.D. degree candidate at the University of Nebraska.

ACKNOWLEDGMENTS

We acknowledge the helpful reviews of an earlier draft of this manuscript by Drs. A. A. Berryman, Washington State University, Pullman; J. L. Foltz, University of Florida, Gainesville; R. A. Haack, Michigan State University, East Lansing; M. W. Stock, University of Idaho, Moscow; and R. N. Coulson and T. L. Wagner, Texas A. & M. University, College Station. We also gratefully acknowledge assistance from C. E. Jensen (now retired), Intermountain Research Station, Ogden, in developing the three-dimensional relationships in the data, describing them algebraically, and reviewing the manuscript.

RESEARCH SUMMARY

Some effects of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) phloem thickness on mountain pine beetle (*Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]) were studied in relation to beetle attack and gallery densities. Brood production was positively related to phloem thickness, beetle attack density, and egg gallery density, but showed an asymptotic relationship at high attack and gallery densities. Female length was positively related to phloem thickness but negatively related to increasing egg gallery density. Significantly greater proportions of females emerged from medium and thick phloem than from thin phloem, but sex ratio was not related to attack density. The time of emergence was delayed in thin phloem compared to medium and thick phloem.

June 1986
Intermountain Research Station
324 25th Street
Ogden, UT 84401

Mountain Pine Beetle in Ponderosa Pine: Effects of Phloem Thickness and Egg Gallery Density

Gene D. Amman
Judith E. Pasek

INTRODUCTION

The mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]) kills more pine trees in the Western United States than any other insect. During epidemics, the beetle frequently kills over a million trees a year in a single National Forest (Klein and others 1979) or National Park (McGregor and others 1978).

Hopkins (1909) observed during an outbreak that as a rule the largest and best trees are attacked first—lodgepole (*Pinus contorta* Dougl.) and ponderosa (*P. ponderosa* Dougl. ex Laws.) pines. He further states that "it is only in the thicker bark on the lower portion of the trunk of the medium to larger trees [lodgepole pine] that beetle broods will reach their best development." Craighead and others (1931) state: "In contrast to the trees [lodgepole pine] selected under endemic conditions, it is the larger thick-barked trees that are first attacked during epidemics." The reason for this has been related to thick phloem, the food of beetle larvae, in such trees (Amman 1969). Beetle production, measured as beetle emergence holes, in lodgepole was directly related to crevice thickness of bark on the dead trees. Amman (1969) also showed phloem thickness on living lodgepole pine was highly correlated with bark crevice thickness and suggested that beetle production is dependent on phloem thickness of the infested tree. Subsequently, in a laboratory study, positive correlations between beetle production and phloem thickness were demonstrated (Amman 1972a; Amman and Pace 1976). Phloem thickness of the host tree may also be important in dynamics of other bark beetles. Haack and others (1984) found significant correlations between egg gallery construction and oviposition of *Ips calligraphus* (Germar) and thickness of slash pine (*P. elliottii* Engelm.) phloem.

Because of the significant role phloem thickness plays in the dynamics of MPB in lodgepole pine forests, similar studies were initiated in ponderosa pine, another important host of the beetle and one in which losses continue to be high (McGregor 1985). Blackman (1931) related MPB brood production in ponderosa pine to crown characteristics and rainfall. Under conditions of normal rainfall, trees having heavy crowns produced 42 percent more beetles than trees of medium crowns, and 92 percent more beetles than trees of light crowns. This relationship to crown characteristics during normal rainfall suggests that phloem thickness may be involved because trees having large crowns are probably the most vigorous and would have the thickest phloem. Cole (1973) found lodgepole phloem thickness to be significantly and positively correlated with characteristics of good tree vigor. Therefore, a study of MPB brood production in ponderosa pine of different phloem thickness was conducted. The objectives of the study were (1) to determine beetle brood production in relationship to phloem thickness, beetle attack density, and egg gallery density, and (2) to determine effects of phloem thickness and attack and gallery densities on beetle size, sex ratio, and rate of emergence.

MATERIALS AND METHODS

Three uninfested ponderosa pine trees (one with thin phloem, one with medium, and one with thick) were felled on the Ashley National Forest in northeastern Utah in November 1979. In addition, three infested trees were felled at the same place and time. Billets 50 cm long were cut from each tree and taken to our laboratory in Ogden, UT, where the ends of the billets were waxed to slow moisture loss. Uninfested billets were stored at 2 °C. Infested billets were kept at room temperatures of 20 to 27 °C so immature beetles could complete development and emerge.

In January 1980, we delineated 25 areas (15.2 cm wide by 30.5 cm tall) on uninfested billets taken from each of the three trees. Phloem thickness measurements were made in the center of the four sides of each of the 25 areas from each tree. Mean phloem thickness for each tree was thin ($\bar{x}$ = 1.53 mm; sd = 0.23), medium ($\bar{x}$ = 2.88 mm; sd = 0.43), and thick ($\bar{x}$ = 3.49 mm; sd = 0.44). A 2.5-cm-wide strip of bark was removed from the perimeter of each area to confine developing larvae. Exposed sapwood and bark edges were waxed to slow moisture loss.

To provide a start for egg galleries, vertical holes (5 mm in diameter and 2.5 cm long) were drilled with the long axis of the billet in the bark along the lower edge of each area, and one pair of beetles was introduced into each hole. Sex of beetles was determined by characteristics of the seventh abdominal tergum (Lyon 1958). Holes and beetle introductions were evenly spaced and varied

from one to five per area, depending upon desired attack density. Each attack density was replicated five times in each phloem thickness, resulting in 75 areas.

The newly infested billets were kept upright at room temperatures of 20 to 27 °C and humidity of 20 to 40 percent throughout the experiment, which lasted about 4 months. Plastic screen cages were placed over the infested areas and stapled to the sapwood. A plastic test tube attached to the base of each cage served to catch emerging beetles. Beetles were collected, counted, and sexed daily. Length of each beetle was measured with an ocular micrometer in a dissecting microscope. After emergence was completed, bark was peeled from each of the 75 areas. Bark areas were measured and the area at the base where entrance holes were made was deleted. In addition, area of phloem injured when the tree was felled and thus avoided by beetles was subtracted from bark area. Therefore, the area available to the beetles was less than the approximately 465 cm^2 of each delineated bark area. Remaining beetles, length of egg gallery, and successful attacks (egg gallery starts) were counted. Because egg gallery was not constructed in four areas, analyses were based on the remaining 71 areas. Also, some beetles did not make egg gallery; therefore, numbers of observations in each attack density differed from the five planned in each phloem thickness. To determine if excessive drying of bark and wood occurred during beetle rearing, thus possibly affecting beetle survival, an increment core about 1 inch long was taken from the center of each area with an increment hammer and placed in a glass vial. Moisture content of the wood then

Table 1—Data from study of mountain pine beetle production in ponderosa pine phloem of different

Item		Attack 1			Attack 2			Attack 3		
		x	sd	n	$\bar{x}$	sd	n	$\bar{x}$	sd	n
Brood production (No.)	1[1]	15.20	13.63	9	26.78	11.98	3	25.47	16.19	6
	2	36.31	25.64	7	34.51	19.18	3	40.28	19.75	3
	3	34.70	22.85	9	56.64	29.38	3	64.57	32.47	3
Percent female	1	65.2	21.54	9	62.3	7.18	3	67.0	14.77	6
	2	65.5	13.06	7	81.3	9.58	3	69.5	9.18	3
	3	65.0	12.98	9	69.2	6.96	3	62.2	17.74	5
Female length (mm)[2]	1	5.34	.48	65	5.25	.42	31	5.45	.47	67
	2	5.81	.41	120	5.66	.36	75	5.47	.47	68
	3	5.77	.48	152	5.82	.38	81	5.72	.37	147
Fifty percent (days)[3] beetle emergence	1A	92.3	9.31	9	88.7	19.35	3	76.5	1.87	6
	1B	19.1	14.70	9	21.3	13.80	3	14.0	3.58	6
	2A	75.0	5.23	7	78.0	6.00	3	75.7	9.02	3
	2B	11.1	3.02	7	17.0	5.57	3	15.0	7.21	3
	3A	81.1	11.10	9	76.7	6.66	3	74.4	5.41	5
	3B	23.8	10.80	9	19.7	2.52	3	16.0	5.24	5
Egg gallery (m)	1	.48	.29	9	.75	.25	3	.60	.25	6
	2	.48	.19	7	.60	.14	3	.83	.14	3
	3	.49	.30	9	.57	.15	3	.83	.30	3
Phloem thickness (mm)	1	1.45	.28	9	1.60	.26	3	1.56	.28	6
	2	2.91	.28	7	2.81	.54	3	2.98	.51	3
	3	3.51	.44	9	3.72	.13	3	3.50	.23	5
Sapwood moisture (pct)[4] by weight	1	36.7	11.25	9	47.4	26.17	3	32.9	11.66	6
	2	45.5	6.95	7	48.5	7.88	3	32.8	1.55	3
	3	36.5	10.42	9	44.4	9.51	3	49.6	7.17	5

[1]1, 2, and 3 represent thin, medium, and thick phloem, respectively.
[2]Female length is measured from front of the head to tip of the elytra.
[3]A is the number of days for 50 percent of the new adults to emerge, starting from the day parent beetles were introduced into a bark area to oviposit. B is the number of days for 50 percent of the new adults to emerge, starting from the day the first new adult emerged from a bark area.
[4]Sapwood moisture was determined after beetle emergence was completed.

was determined by weighing, drying in an oven, and reweighing the cores.

ANALYSIS OF DATA

The original data were expanded to represent beetles, successful attacks, and egg gallery per 930 cm^2 for ease of comparison with other studies using this size area. Using these data, brood production (BP) was initially subjected to multiple regression screens in two forms, first as a function of phloem thickness (PT) and gallery density (GD), and second using PT and attack density (AD) to determine if effects of GD and AD were similar. Multiple regression screens also were used to test for effects of GD, AD, and PT on beetle size. Graphic and descriptor development procedures follow those specified in Matchacurves 1, 2, and 3 (Jensen 1973; Jensen and Homeyer 1970, 1971). Each three-dimensional model was developed graphically, using trends in the data to arrive at smoothed curve forms. These were fitted through the data by approximate "least deviations." The resulting graphic forms were described algebraically. These descriptors were given a least squares adjustment (< 5 percent in all cases) to their respective data sets.

ANOVA was used to test for differences in percentages (arc sine transform) of new adults that were female, and the Hartley Multiple Range Test was used to test for differences between means (Snedecor 1956).

RESULTS AND DISCUSSION

We concentrated on four results from this study: brood production, MPB size, sex ratio, and emergence time (table 1).

thickness at different beetle attack densities/930 cm^2

density											
	4			5			6			7		
	$\bar{x}$	sd	n	x	sd	n	$\bar{x}$	sd	n	x	sd	n
	6.31	—	1	21.21	8.21	2	30.51	—	1	31.10	15.53	2
	60.43	20.70	7	39.07	—	1	70.91	41.62	2	—	—	—
	61.88	17.23	3	78.53	18.80	3	41.48	—	1	—	—	—
	20.0	—	1	72.6	23.05	2	70.0	—	1	80.7	13.15	2
	69.6	13.12	7	53.8	—	1	53.6	10.04	2	—	—	—
	68.6	3.35	3	68.0	3.14	3	73.8	—	1	—	—	—
	5.40	—	1	5.27	.44	17	5.18	.72	14	5.16	.43	36
	5.47	.42	225	5.21	.46	15	5.34	.52	50	—	—	—
	5.56	.34	93	5.59	.66	110	5.41	.33	30	—	—	—
	104.0	—	1	85.5	17.68	2	80.0	—	1	82.5	7.78	2
	36.0	—	1	15.0	8.49	2	21.0	—	1	20.5	.71	2
	72.6	3.99	7	82.0	—	1	76.0	1.41	2	—	—	—
	11.0	1.83	7	17.0	—	1	13.0	4.24	2	—	—	—
	76.7	3.51	3	69.3	2.89	3	73.0	—	1	—	—	—
	20.7	3.51	3	12.0	4.36	3	17.0	—	1	—	—	—
	1.12	—	1	1.43	.09	2	1.03	—	1	1.69	.19	2
	1.27	.24	7	1.36	—	1	2.10	.06	2	—	—	—
	1.37	.05	3	1.45	.40	3	2.11	—	1	—	—	—
	1.47	—	1	1.44	.31	2	1.78	—	1	1.70	.18	2
	2.87	.31	7	2.49	.31	1	3.09	.59	2	—	—	—
	3.37	.12	3	3.50	.49	3	3.18	—	1	—	—	—
	31.4	—	1	41.6	20.93	2	26.0	—	1	33.2	8.06	2
	39.3	10.92	7	22.1	—	1	28.3	21.21	2	—	—	—
	42.3	9.22	3	28.9	4.09	3	50.1	—	1	—	—	—

Brood Production

A multiple regression screen of brood production as a function of phloem thickness and gallery density showed gallery density (GD) accounted for a larger amount of variance (30 percent) in brood production than did phloem thickness (PT) (20 percent) (table 2). In a second screen, substituting attack density (AD) for GD, PT accounted for a larger amount of variance (20 percent) than AD (13 percent) (table 2). The PT effect in each case was clearly linear, while both GD and AD were quadratic in nature. Each regression was highly significant ($P < 0.005$). With this information as a base, data were partitioned in each case to examine more closely the nature of the generally quadratic effects of GD and AD. The results are shown in figures 1 and 2. Brood production was significantly and positively related to egg gallery density and phloem thickness ($R^2 = 0.55$; $P < 0.01$). For example, at 0.3 m of egg gallery per 930 cm^2, average brood production was 10 for thin phloem, 23 for medium, and 33 for thick (fig. 1). At 2.1 m of egg gallery per 930 cm^2 of bark, brood production was 27 for thin, 56 for medium, and 75 for thick. Brood production reached an asymptote at about 1.5 m of egg gallery per 930 cm^2 with no drop in brood production out to 2.1 m of gallery per 930 cm^2 of bark, the highest egg gallery density observed in the test.

Brood production was significantly related to PT and AD, the combined effect being similar to that of PT and GD ($R^2 = 0.38$; $P < 0.01$). Brood production for seven attacks per 930 cm^2 was 24 in thin phloem, 45 in medium, and 70 in thick. Curves flattened considerably

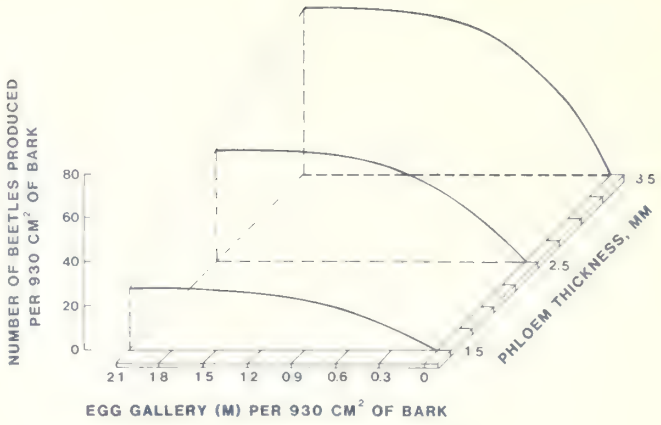


Figure 1—Mountain pine beetle brood production per unit area of ponderosa pine bark increases with both egg gallery density and phloem thickness.

$$BP/930\ cm^2 = 0.9544\ [UI - \frac{UI}{7^n}\ (7 - 3.281\ GD)^n\ ]$$

$UI = (836.766)\ (0.03937\ PT)^{1.2}$
$= \text{upper intercept}$
$n = 2.92 + 83.87\ (0.03937\ PT)^{2.3}$

where

PT = phloem thickness in millimeters
GD = egg gallery density in meters per 930 cm^2
$P < 0.01$
$R^2 = 0.55$
Limits: $0 \leq GD \leq 2.1$.

Table 2—Multiple regression screen of mountain pine beetle brood production as a function of ponderosa pine phloem thickness (PT) and egg gallery density (GD), and ponderosa pine phloem thickness (PT) and attack density (AD)

Phloem thickness - gallery density		Phloem thickness - attack density	
Variables	R^2	Variables	R^2
GD	0.30	AD	0.13
GD^2	.23	AD^2	.08
PT	.20	PT	.20
PT^2	.18	PT^2	.18
GD × GD^2	.35	AD × AD^2	.20
GD × PT	.49	AD × PT	.35
GD × PT^2	.47	AD × PT^2	.33
GD^2 × PT	.40	AD^2 × PT	.30
GD^2 × PT^2	.38	AD^2 × PT^2	.28
PT × PT^2	.48	PT × PT^2	.23
GD × GD^2 × PT	.55	AD × AD^2 × PT	.40
GD × GD^2 × PT^2	.53	AD × AD^2 × PT^2	.38
GD × PT × PT^2	.50	AD × PT × PT^2	.36
GD^2 × PT × PT^2	.56	AD^2 × PT × PT^2	.31
GD × GD^2 × PT × PT^2	.56	AD × AD^2 × PT × PT^2	.41

at three attacks per 930 cm^2 in all three phloem thicknesses (fig. 2). For example in phloem 1.5 mm thick, BP was 19 for three attacks and only 24 for seven attacks; for phloem 3.5 mm thick, BP was 63 for three attacks and 71 for seven attacks. When estimating brood production in wild populations, GD would be preferable to AD because average GD declines with increased AD. In addition, weather can greatly influence gallery length per attack.

The somewhat stronger association of brood production to GD than PT in ponderosa suggests MPB dynamics may be different than in lodgepole, where brood production is strongly associated with PT (Amman 1972a; Amman and Pace 1976). Average BP per 930 cm^2 in phloem 3.5 mm thick is 75 beetles in ponderosa pine in contrast to 112 in lodgepole. Differences in continuity and intensity of infestations, which are generally more severe in lodgepole, may be related to these differences in brood production.

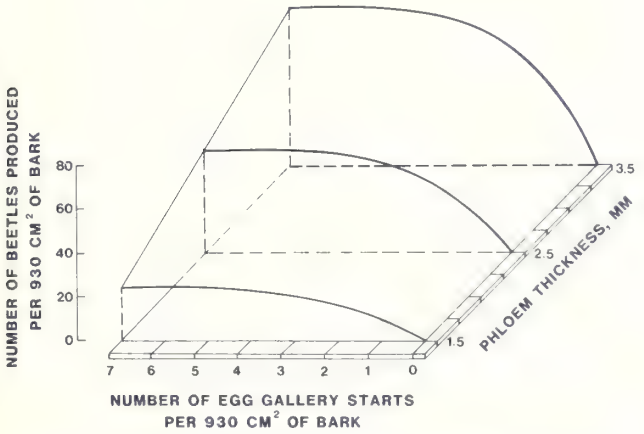


Figure 2—Mountain pine beetle brood production per unit area of ponderosa pine bark increases with both attack density and phloem thickness.

$$BP/930\ cm^2 = 0.9256\ [UI - \frac{UI}{7^n}\ (7 - AD)^n\ ]$$

$UI = (1045.2083)\ (0.03937\ PT)^{1.3}$
$= \text{upper intercept}$
$n = 2.78 + (18.3944)\ (0.03937\ PT)^{1.3}$

where

PT = phloem thickness in millimeters
AD = attack density per 930 cm^2
$P < 0.01$
$R^2 = 0.38$
Limits: $0 \leq AD \leq 7$

Beetle Size

A multiple regression screen showed that female length (FL) was related to the linear effects of PT and GD. In this case, PT accounted for 22 percent ($P < 0.01$) of the variance, and GD accounted for 11 percent ($P < 0.05$) of the variance in FL (table 3). The combined model explained 35 percent ($P < 0.001$) of the variance in FL. The scaled effects are shown in figure 3.

Table 3—Multiple regression screen for length of mountain pine beetle females as a function of ponderosa pine phloem thickness (PT) and egg gallery density (GD)

Variables	R^2
GD	0.11
GD^2	.09
PT	.22
PT^2	.24
GD × GD^2	.12
GD × PT	.35
GD × PT^2	.36
GD^2 × PT	.33
GD^2 × PT^2	.33
PT × PT^2	.24
GD × GD^2 × PT	.35
GD × GD^2 × PT^2	.36
GD × PT × PT^2	.36
GD^2 × PT × PT^2	.35
GD × GD^2 × PT × PT^2	.36

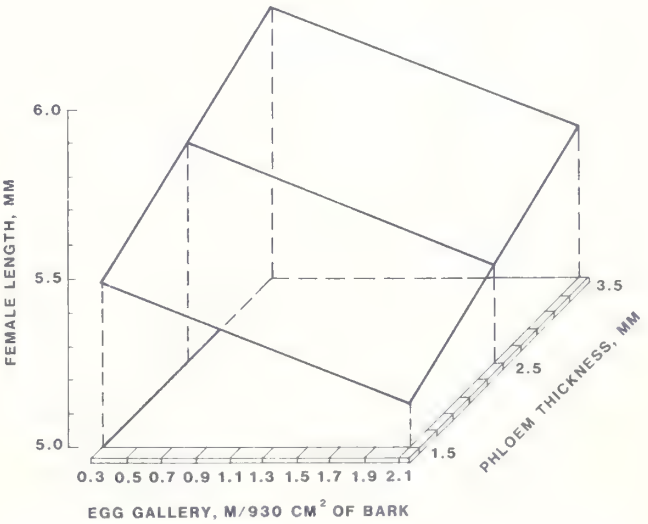


Figure 3—Female mountain pine beetle length declines as egg gallery density increases, but beetle length increases as phloem thickness increases.

$$FL = 5.307 - 0.197\ GD + 0.159\ PT$$

where

FL = female length in millimeters
GD = gallery density in meters per 930 cm^2
PT = phloem thickness in millimeters
$P < 0.01$
$R^2 = 0.35$
Limits: $0.3 \leq GD \leq 2.1$.

Although sizes of both females and males showed the same trend, only female size was analyzed. Average female length at 0.3 m of egg gallery per 930 cm^2 ranged from 5.49 mm for thin phloem to 5.81 mm for thick phloem (fig. 3). At 2.1 m of gallery per 930 cm^2, female length ranged from 5.14 mm in thin phloem to 5.46 mm in thick phloem. Similar relations were observed in lodgepole pine (Amman and Pace 1976). However, beetle size is greater in ponderosa than in lodgepole for any specified combination of phloem thickness and egg gallery density, which suggests that ponderosa phloem is qualitatively better food than lodgepole phloem for mountain pine beetles. Even when MPB of a single population from lodgepole pine were reared in ponderosa and lodgepole pines, those from ponderosa were significantly larger than those from lodgepole (Amman 1982). Two effects associated with small MPB are oviposition of fewer eggs and smaller eggs than occurs with large beetles (Amman 1972b; McGhehey 1971; Reid 1962).

Sex Ratio

The percentages of new adult beetles that were female were not significantly correlated ($P > 0.05$) with attack density in any of the three phloem thicknesses. Therefore, comparisons were made between percentages of beetles that were female from all attack densities. The percentage of new adult beetles that were female did not differ significantly ($P > 0.05$) between thick (66.8 percent) and medium (67.0 percent) phloem, but was significantly less ($P < 0.005$) in thin phloem (62.9 percent). Factors that adversely affect developing MPB generally result in lower survival of males than females. For example: drying (Amman and Rasmussen 1974; Cole and others 1976), cold storage (Safranyik 1976; Watson 1971), and thin phloem (Amman and Pace 1976) in lodgepole pine. The reduced percentage of females coming from thin rather than thick ponderosa pine phloem is just the opposite from the trend observed in lodgepole pine, where thin phloem yielded 72 percent female and thick phloem 66 percent female (Amman and Pace 1976). No explanation is offered for this apparent reversal. Additional observations are planned to determine if this difference in sex ratio between beetles from thick and thin ponderosa phloem is consistent.

Emergence Time

Emergence time of new adults was unrelated to attack density except in thick phloem, where a significant negative correlation occurred ($P < 0.05$). Therefore, emergence times for all beetles, regardless of attack density, were combined for each phloem thickness.These data showed that emergence of beetles from thin phloem was delayed from that of beetles in medium and thick phloem. The time interval for 50 percent of the beetles, starting from introduction of parent adults into the bark areas, was approximately 82 days in thin phloem compared to 71 days in medium, and 75 in thick phloem. The delay in thin phloem is even more apparent later in the emergence cycle (fig. 4).

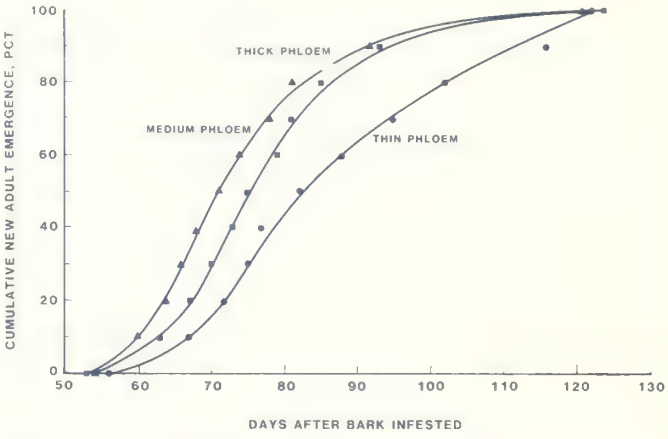


Figure 4—Cumulative percentage of mountain pine beetle emergence from three thicknesses of ponderosa pine phloem (hand-fitted curves).

The differences in time of emergence may be due to nutrition, with medium to thick phloem being best for beetle development. Larvae feeding in thin phloem, particularly those in later instars, probably are chewing outer bark and sapwood in addition to phloem as they feed, thus delaying development. These tissues probably are not as nutritious as phloem, which is readily available to larvae feeding in medium to thick phloem. The rate of beetle emergence was also slower in thin than in thick lodgepole pine phloem (Amman and Cole 1983).

CONCLUSION

The significant association of MPB brood production, beetle size, sex ratio, and time of emergence to phloem thickness in ponderosa pine indicates phloem thickness is an important factor in MPB dynamics in ponderosa pine forests.

REFERENCES

Amman, Gene D. Mountain pine beetle emergence in relation to depth of lodgepole pine bark. Research Note INT-96. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1969. 8 p.

Amman, Gene D. Mountain pine beetle brood production in relation to thickness of lodgepole pine phloem. Journal of Economic Entomology. 65: 138-140; 1972a.

Amman, Gene D. Some factors affecting oviposition behavior of the mountain pine beetle. Environmental Entomology. 1: 691-695; 1972b.

Amman, Gene D. Characteristics of mountain pine beetles reared in four pine hosts. Environmental Entomology. 11: 590-593; 1982.

Amman, Gene D.; Cole, Walter E. Mountain pine beetle dynamics in lodgepole pine forests. Part II: population dynamics. General Technical Report INT-145. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 59 p.

Amman, Gene D.; Pace, Vincent E. Optimum egg gallery densities for the mountain pine beetle in relation to lodgepole pine phloem thickness. Research Note INT-209. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1976. 8 p.

Amman, Gene D.; Rasmussen, Lynn A. A comparison of radiographic and bark-removal methods for sampling of mountain pine beetle populations. Research Paper INT-151. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1974. 11 p.

Blackman, M. W. The Black Hills beetle. Technical Publication 36. Syracuse, NY: Syracuse University, New York State College of Forestry; 1931. 77 p.

Cole, Dennis M. Estimation of phloem thickness in lodgepole pine. Research Paper INT-148. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 10 p.

Cole, Walter E.; Amman, Gene D.; Jensen, Chester E. Mathematical models for the mountain pine beetle-lodgepole pine interaction. Environmental Entomology. 5: 11-19; 1976.

Craighead, F. C.; Miller, J. M.; Evenden, J. C.; Keen, F. P. Control work against bark beetles in western forests and an appraisal of its results. Journal of Forestry. 29: 1001-1018; 1931.

Haack, Robert A.; Wilkinson, Robert C.; Foltz, John L.; Corneil, Jeffrey A. Gallery construction and oviposition by *Ips calligraphus* (Coleoptera: Scolytidae) in relation to slash pine phloem thickness and temperature. Canadian Entomologist. 116: 625-632; 1984.

Hopkins, A. D. Practical information on the scolytid beetles of North American forests. I. Bark beetles of the genus *Dendroctonus*. Bulletin 83, part I. Washington, DC: U.S. Department of Agriculture, Bureau of Entomology; 1909. 169 p.

Jensen, Chester E. Matchacurve-3: multiple-component and multidimensional mathematical models for natural resource studies. Research Paper INT-146. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 42 p.

Jensen, Chester E.; Homeyer, J. W. Matchacurve-1 for algebraic transforms to describe sigmoid- or bell-shaped curves. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1970. 22 p.

Jensen, Chester E.; Homeyer, J. W. Matchacurve-2 for algebraic transforms to describe curves of the class X^n. Research Paper INT-106. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1971. 39 p.

Klein, William H.; Bennett, Dayle D.; Young, Robert W. A pilot survey to measure annual mortality of lodgepole pine caused by the mountain pine beetle. Report 78-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region and Methods Applications Group; 1979. 15 p.

Lyon, R. L. A useful secondary sex character in *Dendroctonus* bark beetles. Canadian Entomologist. 90: 582-584; 1958.

McGhehey, J. H. Female size and egg production of the mountain pine beetle, *Dendroctonus ponderosae* Hopkins. Information Report NOR-X-9. Edmonton, AB: Canadian Forestry Service, Northern Forest Research Centre; 1971. 18 p.

McGregor, Mark D. Mountain pine beetle: The conflict between people and the beetle. In: Loomis, Robert C.; Tucker, Susan; Hofacker, Thomas H., eds. Insect and disease conditions in the United States 1979-83. General Technical Report WO-46. Washington, DC: U.S. Department of Agriculture, Forest Service; 1985: 16-23.

McGregor, M. D.; Hamel, D. R.; Kohler, S. Status of mountain pine beetle infestations, Glacier National Park and Glacier View Ranger District, Flathead National Forest, Montana, 1977. Report 78-6. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region; 1978. 14 p.

Reid, R. W. Biology of the mountain pine beetle, *Dendroctonus monticolae* Hopkins, in the east Kootenay region of British Columbia. II. Behaviour in the host, fecundity, and internal changes in the female. Canadian Entomologist. 94: 605-613; 1962.

Safranyik, L. Size- and sex-related emergence, and survival in cold storage, of mountain pine beetle adults. Canadian Entomologist. 108: 209-212; 1976.

Snedecor, George W. Statistical methods. Ames, IA: Iowa State College Press; 1956. 534 p.

Watson, J. A. Survival and fecundity of *Dendroctonus ponderosae* (Coleoptera: Scolytidae) after laboratory storage. Canadian Entomologist. 103: 1381-1385; 1971.

U.S. GOVERNMENT PRINTING OFFICE: 1986-0-676-039/41001

Amman, Gene D.; Pasek, Judith E. Mountain pine beetle in ponderosa pine: effects of phloem thickness and egg gallery density. Research Paper INT-367. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986 7 p.

Effects of phloem thickness in ponderosa pine (*Pinus ponderosa*) on mountain pine beetle (*Dendroctonus ponderosae*) were determined in a laboratory study. Brood production, beetle size, sex ratio, and rate of emergence were significantly related to phloem thickness, egg gallery density, and attack density.

KEYWORDS: Scolytidae, bark beetles, *Dendroctonus ponderosae*, phloem, *Pinus ponderosa*

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

A 13.78: Int - Research Papers No. 368 and 369 are available on microfiche. It is located in the fiche cabinets on third floor.

Both publications received – in tackbinder following this volume.

United States
Department of
Agriculture

Forest Service

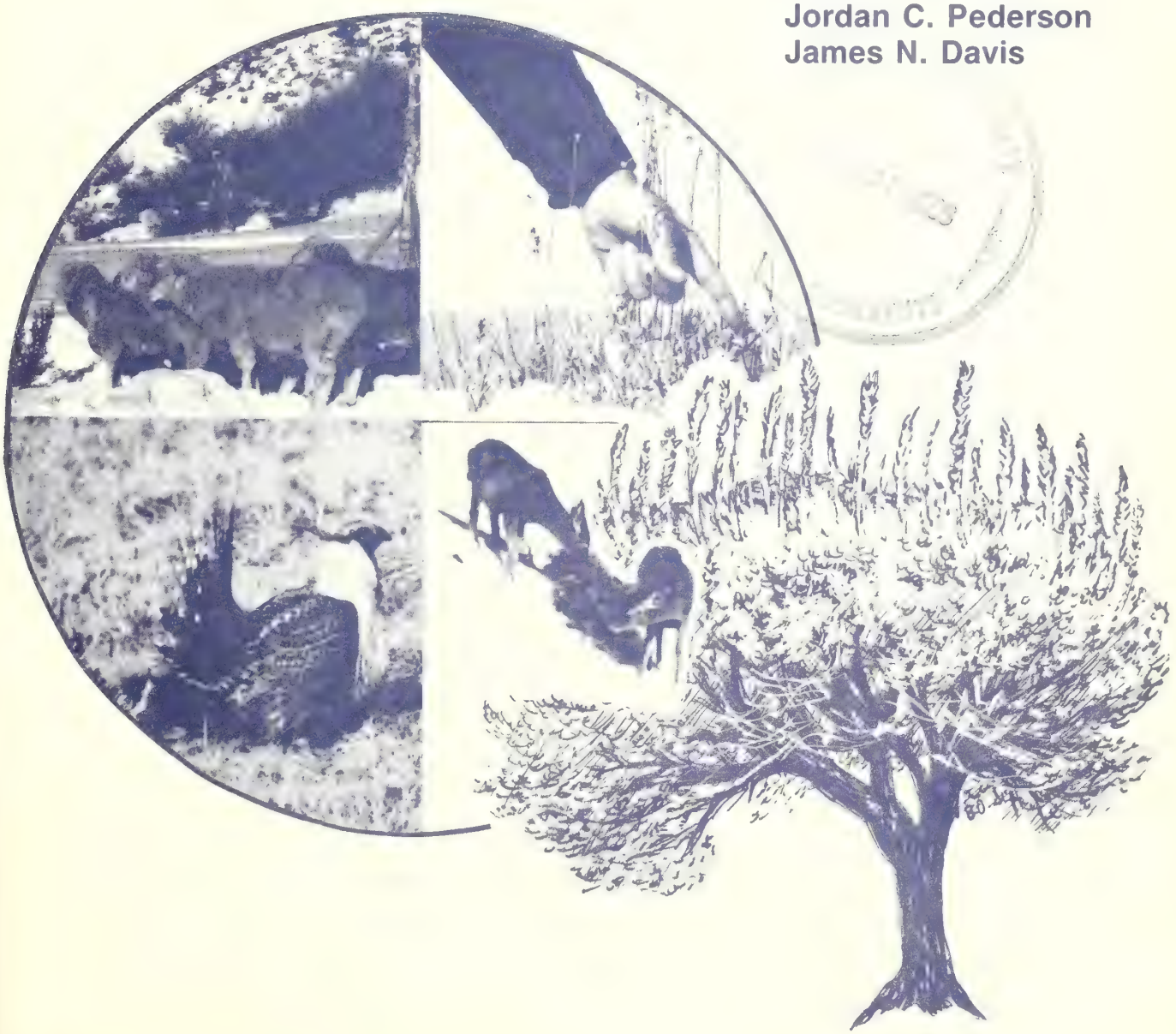
**Intermountain
Research Station**

Research Paper
INT-370

September 1986

'Hobble Creek'— A Superior Selection of Low-Elevation Mountain Big Sagebrush

Bruce L. Welch
E. Durant McArthur
David L. Nelson
Jordan C. Pederson
James N. Davis



THE AUTHORS

BRUCE L. WELCH is a principal plant physiologist with the Intermountain Research Station, Provo, UT. He earned a B.S. degree in agriculture education from Utah State University in 1965, an M.S. degree in animal science from the University of Idaho in 1969, and a Ph.D. degree in plant science from the University of Idaho in 1974. He has served as a Forest Service research scientist on the Shrub Improvement and Revegetation research work unit since 1977.

E. DURANT McARTHUR is a supervisory research geneticist with the Intermountain Research Station, Provo, UT. He earned a B.S. degree in genetics and cytology from the University of Utah in 1965, an M.S. degree in molecular and genetic biology from the University of Utah in 1967, a Ph.D. degree in biology from the University of Utah in 1970, and completed a postdoctorate program in plant genetics at the University of Leeds in 1970-71. He has served as a Forest Service scientist since 1972, studying the genetics of wildland shrubs. Since 1983, he has been project leader for the Shrub Improvement and Revegetation research work unit.

DAVID L. NELSON is a research plant pathologist with the Intermountain Research Station, Provo, UT. He earned his B.S. degree in botany and plant pathology from Utah State University in 1961, an M.S. degree in plant pathology from Utah State University in 1963, and a Ph.D. degree in plant pathology from the University of California at Berkeley in 1971. He has served as a Forest Service research scientist since 1970 studying rust disease problems on conifers and disease problems on wildland shrubs.

JORDAN C. PEDERSON is a game manager with the Central Region of the Utah Division of Wildlife Resources, Springville, UT. He earned a B.S. degree in animal sciences from Brigham Young University in 1964, an M.S. degree in biology from the University of Utah in 1970, and a Ph.D. degree in wildlife and range resources from Brigham Young University in 1985. He has served as a wildlife biologist, research biologist, and game manager for the Utah Division of Wildlife Resources for over 20 years.

JAMES N. DAVIS is a research wildlife biologist with the Utah Division of Wildlife Resources stationed at the Intermountain Research Station, Provo, UT. He earned a B.S. degree in zoology/ecology from Brigham Young University in 1973 and an M.S. degree in botany/ecology from Brigham Young University in 1976, and is finishing a Ph.D. degree in botany/ecology from Brigham Young University. He has served as a wildlife biologist and as a research wildlife biologist with the Utah Division of Wildlife Resources for over 10 years.

ACKNOWLEDGMENTS

The authors express their gratitude to the following individuals for their encouragement over the years to search out superior selections of big sagebrush: James P. Blaisdell, R. Duane Lloyd, A. Perry Plummer, Arthur R. Tiedemann, Norman V. Hancock, S. Dwight Bunnell, Gordon A. Van Epps, Alma H. Winward, Jerran T. Flinders, Jack R. Carlson, Wendell G. Hassell, Sam E. Stranathan, Gary L. Noller, Donald R. Christensen, Bruce C. Giunta, Richard Stevens, Stephen B. Monsen, Ralph C. Holmgren, Arthur D. Smith, Robert L. Elderkin, Kent R. Jorgensen, Nancy Shaw, and Gary L. Jorgensen. Thanks are also extended to Richard Williams of the Heber District of the Forest Service, U.S. Department of Agriculture, for the sage grouse photo used on the cover, and to Ronald L. Rodriguez of the Shrub Sciences Laboratory, Intermountain Research Station, Forest Service, for the sheep photo. Partial funding was provided by Utah Division of Wildlife Resources, Pittman-Robertson Wildlife Restoration Funds W-82-R Jobs 1 and 5, and the Central Regional Office of the Utah Division of Wildlife Resources.

RESEARCH SUMMARY

This is the foundation document for the release of the 'Hobble Creek' selection of big sagebrush. It is a low-elevation mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*). 'Hobble Creek' is needed to increase the nutrient content of winter diets of mule deer (*Odocoileus hemionus hemionus*) and domestic sheep (*Ovis aries*). This sagebrush exceeds the typical winter forage values in amount of energy-producing compounds, crude protein, phosphorus, and carotene. Of the 186 big sagebrush selections tested, 'Hobble Creek' is the most preferred by wintering mule deer and ranks high in preference by wintering domestic sheep. 'Hobble Creek' does not contain substances that lower grass cell wall digestion in ruminant animals.

'Hobble Creek' can be established and maintained on sites that have deep, well-drained soils with an annual precipitation of at least 14 inches (and preferably more). Soil textures should not be any finer than a clay loam (40 percent clay or less). Soil pH may vary from 6.6 to 8.6.

'Hobble Creek' can be established by direct seeding, by transplanting bareroot or containerized stock, and by a technique we term "mother plant."

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture or Utah Division of Wildlife Resources of any product or service.

September 1986
Intermountain Research Station
324 25th Street
Ogden, UT 84401

'Hobble Creek'—A Superior Selection of Low-Elevation Mountain Big Sagebrush

Bruce L. Welch
E. Durant McArthur
David L. Nelson
Jordan C. Pederson
James N. Davis

THE NEED

Forages on mule deer (*Odocoileus hemionus hemionus*) and domestic sheep (*Ovis aries*) winter ranges are low in energy, protein, phosphorus, and carotene. This is illustrated in table 1 (common and scientific names in the table and text are from Plummer and others 1977). Most of the forages listed are below the maintenance requirement for these nutrients (National Academy of Sciences 1975). Maintenance requirement is the level of nutrients needed to prevent loss of animal weight. Using in vitro digestibility as a measurement of energy, an in vitro digestibility of about 50 percent is needed for maintenance of wintering mule deer and domestic sheep (Ammann and others 1973). Of the 29 forages listed in table 1, only seven meet the maintenance level with most falling substantially below the maintenance need. The crude protein maintenance requirement for mule deer and sheep is 7.0 to 8.9 percent of dry matter (National Academy of Sciences 1975; Welch and McArthur 1979a). Of the forage species listed in table 1, only 11 meet the required protein maintenance level. The phosphorus maintenance requirement for mule deer and sheep ranges from 0.18 to 0.28 percent of dry matter (National Academy of Sciences 1975; Welch and McArthur 1979a). Only one forage meets the upper level for phosphorus and three meet the lower level. For carotene, the maintenance requirement is 2.0 mg/kg of dry matter (National Academy of Sciences 1975; Welch 1983). Only five forages meet or exceed this need.

Mule deer and domestic sheep winter ranges need forages that supply energy-producing compounds, crude protein, phosphorus, and carotene at or above the maintenance level. Only three forages—fall regrowth of crested wheatgrass (*Agropyron desertorum*), black sagebrush (*Artemisia nova*), and big sagebrush (*Artemisia tridentata*)—exceed the maintenance requirement for energy-producing compounds, crude protein, and carotene. Phosphorus levels of big sagebrush are midrange of the need. Big sagebrush not only can increase the nutrient level of winter diets, but it is a more dependable forage source during periods of drought than are other shrubs, forbs, or grasses (Medin and Anderson 1979; McArthur and Welch 1982).

It is, in part, the evergreen (high leaf-to-twig ratio) nature of big sagebrush that gives it a winter nutritional advantage over deciduous shrubs such as bitterbrush (*Purshia tridentata*) and true mountain-mahogany (*Cercocarpus montanus*) and most herbaceous species. Big sagebrush is ecologically adapted to many of our spring-fall-winter ranges (McArthur and Plummer 1978). Big sagebrush usually remains available for use above the snow while the other forage classes become covered and unavailable for wintering animals. Not all big sagebrush populations are equally preferred by wintering animals or are equal in nutritive content (Welch 1983).

What follows is a description of the nutritive profile of 'Hobble Creek', a superior selection of low-elevation mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*).

THE NUTRITIVE PROFILE

In two studies, the 'Hobble Creek' selection was preferred over other selections by wintering mule deer (Welch and others 1981; Welch and McArthur 1986b). This preference is illustrated in table 2. Preference was measured in terms of the percentage of current year's growth removed. Table 2 shows that mule deer from three herds removed significantly greater percentage of the current year's growth from 'Hobble Creek' than from the other 20 selections. A research cooperator testing it against native big sagebrush reported that mule deer in his area (Colorado) heavily favored 'Hobble Creek' (Elderkin 1986).

Preference of wintering domestic sheep for the 'Hobble Creek' selection is illustrated in table 3. The sheep had continual access to high-quality alfalfa hay and 0.75 lb of rolled barley per day per head. The sheep were not starved onto the big sagebrush, but ate big sagebrush by choice. 'Hobble Creek' was in the most preferred group of big sagebrush selections at 80.6 percent of the current year's growth consumed (Welch and others, in press).

Studies show that the productivity of 'Hobble Creek' ranks in the top third of selections tested. Productivity expressed as length of leader growth is illustrated in table 4 (McArthur and Welch 1982; Welch and McArthur 1986a). Of the 21 selections, 'Hobble Creek' ranked seventh and was significantly exceeded only by five selections of *A. tridentata* ssp. *tridentata*. Davis and Stevens (1986) reported that 'Hobble Creek' ranked third out of 20 selections in vegetative production (g/cm of stem).

Winter crude protein content of 'Hobble Creek' is 11 percent of dry matter. This ranks it high among the winter range forages listed in table 1, but as a big sagebrush its crude protein level is below the average of those

Table 1—Winter nutritive value[1] of selected range plants; data expressed as a percentage of dry matter except carotene, which is expressed as milligrams per kilogram of dry matter

Plant name (common and scientific[2])	In vitro digestibility	Crude protein	Phosphorus	Carotene
	Percent			mg/kg
Grasses				
Bearded bluebunch wheatgrass *Agropyron spicatum*	45.5	3.2	0.05	0.22
Bluestem wheatgrass *A. smithii*	50.2	3.8	.07	.20
Bottlebrush squirreltail *Sitanion hystrix*	42.0	4.3	.07	1.10
Crested wheatgrass *A. desertorum*	43.1	3.5	.07	.20
Crested wheatgrass, fall regrowth *A. desertorum*	50.6	15.0	.39	432.00
Galleta *Hilaria jamesii*	48.2	4.6	.08	.40
Idaho fescue *Festuca idahoensis*	50.5	3.8	.08	—
Indian ricegrass *Oryzopsis hymenoides*	50.5	3.1	.06	.44
Reed canarygrass *Phalaris arundinacea*	—[3]	7.8	.14	—
Needle-and-thread grass *Stipa comata*	46.6	3.7	.07	.40
Sandberg bluegrass *Poa secunda*	—	4.2	—	—
Sand dropseed grass *Sporobolus cryptandrus*	53.2	4.1	.07	.50
Smooth brome *Bromus inermis*	47.0	4.1	.12	—
Shrubs				
Antelope bitterbrush *Purshia tridentata*	23.5	7.6	.14	—
Big sagebrush *Artemisia tridentata*	57.8	11.7	.22	17.6
Black sagebrush *Artemisia nova*	53.7	9.9	.18	8.0
Common winterfat *Ceratoides lanata*	43.5	10.0	.11	16.8
Curlleaf mountain-mahogany *Cercocarpus ledifolius*	49.1	10.1	—	—
Forage kochia *Kochia prostrata*	32.2	7.2	—	—
Fourwing saltbush *Atriplex canescens*	38.3	8.9	—	3.1
Gambel oak *Quercus gambelii*	26.6	5.3	—	—
Low rabbitbrush *Chrysothamnus viscidiflorus*	36.0	5.9	.15	—
True mountain-mahogany *Cercocarpus montanus*	26.5	7.8	.13	—
Rubber rabbitbrush *Chrysothamnus nauseosus*	44.4	7.8	.14	—
Cliffrose *Cowania mexicana*	37.6	8.6	—	—
Utah juniper *Juniperus osteosperma*	44.1	6.6	.18	—
Forbs				
Arrowleaf balsamroot *Balsamorhiza sagittata*	—	3.6	.06	—

Table 1—(Con.)

Plant name (common and scientific[2])	In vitro digestibility	Crude protein	Phosphorus	Carotene
	---------- Percent ----------			mg/kg
Oneflower helianthella *Helianthella uniflora*	—	2.8	.17	—
Small burnet *Sanguisorba minor*	—	6.6	—	—

[1]Values represent the average of a number of studies reported in the literature. References are on file at the Intermountain Research Station's Shrub Sciences Laboratory, Provo, UT.
[2]Common and scientific names after Plummer and others (1977).
[3]A bar means no information available.

Table 2—Preference of three wintering mule deer herds for selections of big sagebrush (*Artemisia tridentata*) grown on three geographically separate gardens. Data expressed as a percent of current year's growth eaten. Data points are means for three gardens and 3 years. (Data from Welch and McArthur 1986b)

Selections	Percent of current year's growth eaten
HOBBLE CREEK (v)[1]	57.5[a2]
Colton (v)	47.0[b]
Petty Bishop's Log (v)	46.0[b]
Indian Peaks (v)	45.6[bc]
Sardine Canyon (v)	44.6[bc]
Salina Canyon (v)	41.7[bcd]
Durkee Springs (v)	40.7[bcde]
Evanston (w)	40.4[bcde]
Pinto Canyon (v)	40.3[bcdef]
Benmore (v)	39.3[bcdefg]
Clear Creek Canyon (v)	38.4[cdefg]
Milford (w)	37.1[cdefg]
Wingate Mesa (t)	36.4[defgh]
Brush Creek (t)	35.7[defgh]
Dog Valley (t)	33.8[defgh]
Kaibab (w)	33.5[efgh]
Loa (t)	31.6[fgh]
Clear Creek Canyon (t)	31.3[gh]
Dove Creek (t)	30.9[h]
Trough Springs (w)	30.1[h]
Evanston (t)	28.3[h]

[1]v = *Artemisia tridentata* ssp. *vaseyana*; t = *A. t.* ssp. *tridentata*; w = *A. t.* ssp. *wyomingensis*.
[2]Means sharing the same superscript are not significantly different at the 5 percent level.

Table 3—Wintering domestic sheep preference for selections of big sagebrush (*Artemisia tridentata*) grown on three uniform gardens. Data expressed as percent of current year's growth eaten. Data are a summary of three gardens—30 replications per selection. (Data from Welch and others in press)

Selections	Percent of current year's growth eaten
Kaibab (w)[1]	98.3[a2]
Colton (v)	92.3[a]
Trough Springs (w)	91.1[a]
Wingate Mesa (t)	85.9[ab]
Milford (w)	82.7[ab]
Brush Creek (t)	81.7[ab]
HOBBLE CREEK (v)	80.6[ab]
Pinto Canyon (v)	76.7[b]
Sardine Canyon (v)	58.1[c]
Petty Bishop's Log (v)	48.6[cd]
Evanston (w)	44.2[cde]
Indian Peaks (v)	39.8[cdef]
Clear Creek (v)	21.7[ef]
Benmore (v)	16.7[efg]
Durkee Springs (v)	16.0[g]
Salina Canyon (v)	10.9[fg]
Dog Valley (t)	4.4[g]
Clear Creek (t)	1.9[g]
Evanston (t)	0.5[g]
Loa (t)	0.0[g]
Dove Creek (t)	0.0[g]

[1]v = *Artemisia tridentata* ssp. *vaseyana*; t = *A. t.* ssp. *tridentata*; w = *A. t.* ssp. *wyomingensis*.
[2]Means sharing the same superscript are not significantly different at the 5 percent level.

Table 4—Mean leader lengths of 21 selections of big sagebrush grown on three sites for 5 years (10 plants per selections per site). Data are expressed as centimeters of current year's growth. (Data from Welch and McArthur 1986a)

Selections	Length
	cm
Dove Creek (t)[1]	41.4[a2]
Loa (t)	33.1[b]
Dog Valley (t)	33.0[b]
Evanston (t)	30.9[c]
Clear Creek Canyon (t)	30.8[c]
Pinto Canyon (v)	23.2[d]
HOBBLE CREEK (v)	23.1[de]
Salina Canyon (v)	23.0[de]
Indian Peaks (v)	20.9[efg]
Wingate Mesa (t)	20.7[efg]
Kaibab (w)	20.7[efg]
Durkee Springs (v)	20.6[efg]
Sardine Canyon (v)	20.2[fg]
Clear Creek Canyon (v)	18.8[gh]
Benmore (v)	18.8[gh]
Milford (w)	17.2[hi]
Colton (v)	17.2[hi]
Brush Creek (t)	16.7[hi]
Evanston (w)	15.8[i]
Trough Springs (w)	15.5[i]
Petty Bishop's Log (v)	15.3[i]

[1]v = *Artemisia tridentata* ssp. *vaseyana*; t = *A. t.* ssp. *tridentata*; w = *A. t.* ssp. *wyomingensis*.

[2]Means sharing the same superscript are not significantly different at the 5 percent level.

Table 5—Midwinter crude protein content of current year's growth among selections of big sagebrush. Data expressed on a dry-matter basis. No statistical comparisons on a selection basis were made (Welch 1983)

Selections	Percentage of crude protein
Dove Creek (t)[1]	16.0
Clear Creek Canyon (t)	15.3
Evanston (t)	15.2
Dog Valley (t)	14.5
Loa (t)	14.5
Brush Creek (t)	13.1
Evanston (w)	12.9
Wingate Mesa (t)	12.8
Colton (v)	12.0
Kaibab (w)	11.9
Salina Canyon (v)	11.7
Alton (v)	11.3
Milford (w)	11.2
Petty Bishop's Log (v)	11.2
Indian Peaks (v)	11.2
HOBBLE CREEK (v)	11.0
Trough Springs (w)	11.0
Pinto Canyon (v)	11.0
Sardine Canyon (v)	10.5
Durkee Springs (v)	10.0
Benmore (v)	10.0

[1]v = *Artemisia tridentata* ssp. *vaseyana*, t = *A. t.* ssp. *tridentata*, w = *A. t.* ssp. *wyomingensis*.

tested (Welch and McArthur 1979b). Its ranking among other selections of big sagebrush is illustrated in table 5. 'Hobble Creek' winter crude protein still exceeds the maintenance requirement (7 to 8.9 percent of dry matter) of mule deer and domestic sheep (National Academy of Sciences 1975; Welch and McArthur 1979a).

Winter in vitro digestibility, an indicator of energy, is 52.6 percent of 'Hobble Creek' dry matter. This ranks it high among the winter range forages listed in table 1, but as a big sagebrush its in vitro digestibility is just below the average of those tested (Welch and Pederson 1981). The ranking of 'Hobble Creek' among other selections of big sagebrush is illustrated in table 6. 'Hobble Creek' in vitro digestibility just exceeds what is thought to be the maintenance requirement (50 percent) for wintering mule deer and domestic sheep (Ammann and others 1973).

Winter level of phosphorus for the selection was 0.21 percent. Even though this is below the upper maintenance requirement of 0.28 percent for wintering mule deer and domestic sheep, it ranks high among other forages (table 1). We have not measured the phosphorus content of other selections of big sagebrush, but based on the data in table 1 for big sagebrush, we believe that 'Hobble Creek' is at least average.

Total winter monoterpenoid (essential or volatile oils) content of 'Hobble Creek' is 2.09 percent of dry matter. This level is about midrange for other selections of big sagebrush (Welch and McArthur 1979a, Welch and McArthur 1981). The 'Hobble Creek' profile consists of six monoterpenoids (table 7): camphene, 1,8 cineol, camphor, Beta-thujone, fenchyl alcohol, and one unidentified oxygenated-monoterpenoid. Camphor makes up about 55 percent of the total monoterpenoids (table 7). Camphor was followed by 1,8 cineol at 28.7 percent. We have not established a significant relationship between monoterpenoid content and preference (White and others 1982; Pederson and Welch 1985; Welch and others 1983) or between monoterpenoids and digestibility (Welch and Pederson 1981; Pederson and Welch 1982). Hobbs and others (1986) reported that large amounts of 'Hobble Creek' vegetative tissue (80 percent of digestion mixture) did not suppress grass cell wall digestion.

AREAS WHERE IT CAN BE GROWN

The native site of 'Hobble Creek' is east of Springville, UT, at the mouth of the Hobble Creek drainage at an elevation of about 4,600 ft. The breeder plot that defines the selection is a 100- by 100-ft enclosure with a southern exposure and a 20 percent slope. Soil environmental conditions within 100 ft of the enclosure were considered to be part of the selection native site.

Table 6—Winter in vitro digestibility of current year's growth from 10 selections of big sagebrush. Data expressed on a percentage of dry matter basis. 'Hobble Creek' not included in the statistical analysis. Data from Welch and Pederson (1981) and on file at the Intermountain Research Station's Shrub Sciences Laboratory, Provo, UT.

Selections	Percent digested dry matter
Clear Creek Canyon (t)[1]	64.8[a2]
Dove Creek (t)	64.6[a]
Loa (t)	57.0[b]
Indian Peaks (v)	55.8[b]
Benmore (v)	55.2[b]
Kaibab (w)	54.9[b]
Milford (w)	54.6[b]
HOBBLE CREEK (v)	52.6
Sardine Canyon (v)	48.7[bc]
Trough Springs (w)	44.6[c]

[1]v = *Artemisia tridentata* ssp. *vaseyana*, t = *A. t.* ssp. *tridentata*, w = *A. t.* ssp. *wyomingensis*.

[2]Means sharing the same superscript are not significantly different at the 5 percent level.

Table 7—Winter monoterpenoid (essential or volatile oils) content of current year's growth of Hobble Creek big sagebrush. Data expressed as a percent of dry matter and as a percent of the total monoterpenoids. (Unpublished data on file at the Intermountain Research Station's Shrub Sciences Laboratory, Provo, UT)

Monoterpenoid	Percent of dry matter	Percent of total monoterpenoids
Camphene	0.05	2.4
I,8 cineol	.60	28.7
Camphor	1.15	55.0
B-Thujone	.10	4.8
Fenchyl alcohol	.02	1.0
Oxygenated unknown	.17	8.1
	2.09	100.0

Here the selection grows on six soils: Bingham gravelly loam, Lakewin cobbley fine sandy loam, Lakewin gravelly fine sand loam, Pleasant Grove sandy loam, Pleasant Grove stony loam, and Sterling-Terrance cobbley fine sand. All soils are deep and well drained. They are usually moist but are dry between the depths of 7 and 20 inches for more than 60 consecutive days in the summer. Soil pH ranges from 7.0 to 8.4. These values represent all soils and soil layers. Weathered limestone is the parent material. From 3 to 4 inches of available water is held in these soils to a depth of 5 ft. Roots can penetrate to a depth of 5 ft or more. Average annual precipitation ranges from 14 to 18 inches. The effective precipitation at the breeder plot is probably less than the 14 to 18 inches due to the southern exposure and 20 percent slope. The frost-free period ranges from 130 to 170 days. All soils are moderate to rapidly permeable with moderate natural fertility (Utah State Engineer Office 1931-60; Swenson and others 1972).

'Hobble Creek' big sagebrush grows and reproduces on other sites. Two of these sites at which the plant has received substantial testing are Salt Creek Canyon and Gordon Creek Wildlife Management Area. The Salt Creek Canyon site is about 2 miles east of Nephi, UT, at an elevation of about 5,500 ft. It is a basin big sagebrush (*A. t.* ssp. *tridentata*) site. Soil is a Rofiss gravelly clay loam, 4 to 5 percent slope. It is a deep, well-drained alluvial soil derived from Arpien shale. Soil permeability is moderately slow with an effective rooting depth of 5 ft or more. Average annual precipitation ranges from 12 to 16 inches; pH ranges from 8.2 to 8.6. The frost-free period is from 100 to 140 days (Utah State Engineer Office 1931-60; Trickley and Hall 1984).

The Gordon Creek Wildlife Management Area is about 7 miles west/southwest of Helper, UT. It is a "nontypical" Wyoming big sagebrush (*A. t.* ssp. *wyomingensis*) site. Soil is of the Atrac series (Atrac is a fine sandy loam that usually occurs on 1 to 6 percent slopes). This soil is a deep, well-drained derivative of sandstone. Because of the sandstone parent material, this soil lacks the calcareous hardpan that is typical for most Wyoming big sagebrush habitat types (Winward 1983). Soil permeability is rapid with an effective rooting depth of 5 ft or more. The pH range is from 6.6 to 8.0. Average annual precipitation ranges from 12 to 14 inches. Frost-free period is 100 to 120 days (Utah State Engineer Office 1931-60; USDA SCS 1981).

'Hobble Creek' has also been grown successfully in Meeker, CO; Piceance Basin, CO; Challis, ID; and Tintic Valley, UT. The driest of these sites is Tintic Valley at 12 inches of annual precipitation (Utah State Engineer Office 1931-60).

'Hobble Creek' big sagebrush can be grown on sites with the following physical characteristics:

1. Mean annual precipitation of 14 or more inches. This is on the low end of the range for mountain big sagebrush (*A. t.* ssp. *vaseyana*). Monsen and McArthur (1985) reported a mean annual precipitation of 16.5 inches for eight Utah mountain big sagebrush communities.
2. Deep, well-drained soils with an effective rooting depth of at least 4 ft.
3. Soil no finer than clay loam (40 percent clay or less). On sites with heavy clay soils, mountain big sagebrush (this includes 'Hobble Creek') appears to be predisposed to root rot and vascular wilt type pathogens and soon dies (Nelson and Krebill 1981).
4. Soil pH between 6.6 and 8.6.
5. Growing season of 90 days or more.

We do not recommend trying to establish 'Hobble Creek' in Wyoming big sagebrush sites because of shallow soils and low precipitation (Winward 1983).

ESTABLISHMENT

'Hobble Creek' big sagebrush can be established on suitable sites by direct seeding, by transplanting bareroot or containerized stock, and by a technique we term "mother plant." Descriptions of the establishment techniques follow.

Direct Seeding

Direct seeding is the most practical method for establishing 'Hobble Creek' on areas larger than 10 acres. A successful direct-seeding program starts with the seed. Wildland seed quality and quantity varies greatly between years even if collected from the same site. 'Hobble Creek' seed is ready for collecting between mid-November and early December on the native site. This is also true for the 'Hobble Creek' seed increase plot located at Meeker, CO. However, due to the effects of heavy mule deer use, the native site is not a dependable source of 'Hobble Creek' seed. In one study, mature plants protected from heavy grazing (70 percent or more of the current year's growth) produced 30 to 50 times more seed stalks, and the stalks were 2 inches longer than the heavily grazed plants (Rodriguez and Welch 1986). Also, non-'Hobble Creek' big sagebrush needs to be kept 150 ft away from the seed garden to minimize or eliminate cross-pollination.

Harvesting 'Hobble Creek' seed from seed increase gardens can be accomplished by two hand techniques. One technique is to use sticks and to beat the ripened seed from the plants onto hand-held canvas hoppers. After proper drying, this material is run through a barley debearder. This procedure breaks stems so that seed cleaning is facilitated. However, it should be done rapidly so that seeds are not overheated. Further cleaning by passing materials through a series of screens will remove larger inert materials. This technique is fast but does not collect all available seed and will not work on less than fully ripened seed. When stormy weather is approaching and the seed is not fully ripened or to maximize the amount of seed harvested, another technique may be needed. The alternate technique is to cut the seed stalks off with clippers. The seed stalks are placed in heavy-duty plastic bags or other suitable containers and transported to drying racks, benches, or tables. Seed stalks must be air dried to prevent the development of mold and to reduce the tendency to ball up when cleaning the seed. Large stems can be separated from the seed and chaff by hand stripping. After stripping, the seed and chaff are passed through a series of screens that remove the fine stems and larger particles of chaff.

Sagebrush seed is normally collected with about 10 to 15 percent purity (Plummer and others 1968). Greater purities are possible, up to 95 percent and more, if the users are willing to pay the extra cost for cleaning. Storage life of big sagebrush seed in an open warehouse without temperature or humidity controls is about 5 years (Stevens and others 1981). Seed lots must be tested for germinability before being used in a direct seeding program regardless of age.

After a suitable site has been chosen, the next step in a successful direct-seeding program is site preparation. This could be total removal of all existing vegetation or partial removal as with interseeding (strips 2 ft wide, spots 1 ft^2, or small patches). Vegetation can be removed or reduced by wild or prescribed fire, by mechanical means (roto-tillers, plows, disks, harrows, anchor chains, and so forth), or by chemical means. The amount of vegetation removal will depend on the amount and kinds of other forage species to be seeded with the 'Hobble Creek' big sagebrush. Seedbed preparation for big sagebrush is not as intense as for other forage species. It requires only competition control during germination and establishment. The amount of seedbed preparation will be dependent on the species in the mixture requiring the greatest amount of soil tilling. We do recommend planting 'Hobble Creek' big sagebrush in mixtures with other forage species because mixtures are more productive than monocultures, are able to extend season of use, and are more resistant to diseases and insects. Winward (1983) pointed out that mountain big sagebrush often occurs in floristically rich plant communities. The mixture should, however, be so constructed that 'Hobble Creek' will be dominant.

After site and seedbed preparation, the next chore is to sow the 'Hobble Creek' or seed mixture. This means choosing the time and depth of seeding. 'Hobble Creek' seed on the native site is wind-dispersed around the first part of December. Therefore, we believe the optimum time to sow the seed is just before the first accumulation of snow (see Young and Evans 1986 for additional information). Most species that are desirable to be planted with 'Hobble Creek' can also be sowed at this time.

Planting depth will vary according to species. For 'Hobble Creek,' surface or near-surface sowing on a firm seedbed is recommended. In greenhouse studies seedling emergence is near zero when 'Hobble Creek' seeds are planted deeper than 5 mm (Jacobson and Welch 1986). This also appears to be the case with other selections of sagebrush (Kelsey 1986; Young and Evans 1986). Frost heaving and the expansion and contraction of the soil surface due to wetting and drying will apparently cover the sagebrush seed enough for germination and establishment to take place.

'Hobble Creek' seed can be sown by aerial seeders, cyclone seeders, dribblers, and drills that have been adjusted not to cover the seeds. When using a drill, Richardson and others (1986) recommend that sagebrush and other shrubs be planted separately, in different rows, from the grass and forb species. Due to their quick development, grasses and forbs can cause detrimental competition in shrub establishment. This planting technique requires less shrub seed. Competition from the other forages is apparently not as much of a problem when aerially or broadcast seeded onto a prepared seedbed because of the more diverse microhabitat available for seed placement (Young and Evans 1986).

Amount of 'Hobble Creek' seed to be sown is more difficult to recommend and was the source of a vigorous debate among authors and reviewers of this manuscript. The reason for this debate is the lack of definitive studies and a definition of what constitutes a satisfactory sagebrush stand. Published rates range from 0.1 lb per acre to 0.85 lb per acre of pure live seed (Plummer and others 1968; Richardson and others 1986; personal communications). The senior author favors at least 0.25 lb per acre of

pure live seed. This is based partly on the assumption that 'Hobble Creek' is the most important species in the planting mixture. Utah Division of Wildlife Resources recommendations are 1 to 1.5 lb (10 percent purity, minimum of 65 percent germination) per acre which is equivalent to 0.065-0.098 lb of pure live seed per acre in a mixture that includes adapted shrubs, forbs, and grasses. Definitive studies are being planned.

Other direct seeding information: When interseeding behind a modified plow or scraper, best growth was found to be on the most shallow scalping treatment (Stevens 1985). Also, good results have been obtained by spraying strips with a broad-spectrum herbicide such as Round-up® followed by light harrowing and broadcasting the seed on the strip. Seedlings resulting from direct seeding projects may need protection from heavy grazing by wintering domestic sheep or mule deer for 2 or 3 years (Hunter and others 1980).

Transplanting Bareroot and Containerized Stock

Because of the expense, the usefulness of transplanting bareroot or containerized stock is limited to small, critical areas—seed increase gardens or demonstration plots. Planting stock should be from 5 to 8 inches tall and overwintered in a nonheated nursery bed or lathhouse. Actual transplanting can occur as soon as the frost has left the soil and the soil is tillable. We highly recommend spring transplanting of properly hardened planting stock. However, summer transplanting of containerized stock can be successful if the transplants receive adequate irrigation during the first growing season. We do not recommend fall planting of bareroot or containerized stock because of the danger of frost heaving and the lack of dependable soil moisture. Nonhardened containerized planting stock, such as containerized stock grown in a greenhouse during late winter (January to March), needs to receive a couple of water stress treatments before being planted. Planting of this type of stock should be after the possibility of frost. Transplants planted after May 1 may need supplemental watering for the first year. Usually the wettest month of the year is April.

For each transplant, an area 0.5 to 1 ft^2 needs to be cleared only once of all grass, forb, or shrub competition. The key to proper competition elimination is the mixing of the soil and the killing of tops, roots, stolons, and rhizomes. This can be done with hand shovels, a two-operator power posthole digger, tractor posthole digger, and so forth. Soil must be packed firmly around the transplant. To enhance survival, a basin about 0.5 ft in diameter with the plant at the bottom of the basin (1 to 3 inches deep) could be constructed at this point. The basin would serve as a water catchment. For extremely critical areas and during dry periods, the basin could be filled with water. For containerized stock, it is a good practice to cover the top of the greenhouse plant-growing medium with 0.5 inch of native soil. This will prevent the greenhouse medium acting as a wick and drying out the transplant.

We recommend 7 ft of spacing between containerized or bareroot transplants (7- by 7-ft grid equals about 900 plants per acre). This spacing would allow for the growth of desirable understory species of grasses and forbs. Where possible, the transplants should be protected from heavy grazing for two or three growing seasons (Hunter and others 1980). Planting of bareroot or containerized stock can be done with a modified tree planter (Stevens 1985). For those systems using a scalper or plowing action, workers should be careful to minimize removal or hilling of topsoil. Because topsoils are shallow on most western rangelands, excess removal or hilling could result in a great portion of the feeder roots developing in the subsoil, resulting in poor or slow growth. First year survival rates should be in the 80 percent or higher range.

Producing Containerized Stock

In producing containerized 'Hobble Creek' stock, we use a plant-growing medium composed of sphagnum peatmoss, horticultural vermiculite, sandy loam soil, and number 3 sandblasting grit. We screen the peatmoss and soil through 0.5-inch hardware cloth prior to mixing. The plant-growing medium formulation is four parts screened peatmoss, three parts vermiculite, three parts screened soil, and three parts sand. A package of fertilizer is added during mixing of the medium. (Table 8 lists the fertilizers and the quantities used.) Plant-growing medium and fertilizer is thoroughly mixed while dry in a concrete mixer. Next, water is added until the mixture can maintain a ball shape after being hand squeezed. After mixing, the plant-growing medium is transferred to a soil cart where it is treated with aerated steam. This treatment heats the medium to 175 °F for 30 min. Aerated steam treatment controls many soil-borne plant pathogens. We use the methods described by Nelson (1984) to produce disease-free containerized stock.

Next, the medium is cooled and moved into a clean potting room where it is placed in Tinus root-trainer books (21.5 in^3; 1.5 by 2 by 7.25 inches). Tinus and other brands of root-trainer books having longitudinal grooves prevent spiraling of roots, which reduces balling of the roots. Also, the root tips are air pruned, which aids in reducing root balling. These root trainers are placed in sets of eight into wooden crates. We fill the root trainers firmly to 1 inch from the top. This space provides a water basin. We sow about five to eight 'Hobble Creek' big sagebrush seeds on the surface of the plant-growing medium and cover the

Table 8—Fertilizer mixture used in the production of containerized 'Hobble Creek' big sagebrush stock

Fertilizer	Amount[1]
	Grams
Dolomite	176
Ground limestone	176
Horticultural gypsum	100
Calcium nitrate	32
Osmocote (slow release fertilizers N, P, K)	32
Super phosphate	26
Trace elements	5
Chelate iron	2

[1]The amount of fertilizer indicated is for each cubic foot of plant growing medium.

seed 1/8 inch deep with number 3 sandblasting grit. A fogger is used first thing in the morning and last thing at the end of the working day to keep the seed moist until 2 weeks after germination.

For research purposes, we normally start our containerized stock near January 1. We lengthen the day through use of artificial light (14 hours) until mid-April. Greenhouse temperature is set at 72 °F (day) and 58 °F (night). By mid-April the stock is about 6 to 8 inches high and ready for hardening. Hardening is a two-phase process: one of water stressing the plants and another of exposing the plants to unfiltered sunlight and wind. Plants can be fully hardened in about 2 or 3 weeks. For habitat improvement, we recommend starting the containerized stock in July (greenhouse) and hardening in October and winter in a nonheated lathhouse. Stock should be planted on sites after frost has left the soil and the soil is tillable to take advantage of early (April) spring moisture.

The "Mother Plant"

This establishment technique is a combination of transplanting and natural seed dispersal. Transplants furnish the mother plants that in turn supply the seed for dispersal. This technique would be used after a fire or some other process that has destroyed the native sagebrush stand. The absence of residue seed from the native stand would greatly enhance the success of the technique. The "mother plants" are planted as containerized or bareroot stock on a 50- by 50-ft grid throughout the site. Why 50 by 50? Frischknecht (1962) reported that the mean maximum spread of sagebrush from a mother plant was 42 ft. The direction of spread was dependent on prevailing wind. Energy is then directed toward the establishment, maintenance, growth, and protection of the mother plants on an individual plant basis. This may include fertilization, irrigation, fencing, and so forth.

After 3 to 5 years the mother plants are mature enough to produce seed. Direct seeding methods are then applied. Mechanical or chemical means are used to reduce competition either in strips or spots. This technique is needed for stand maintenance where 'Hobble Creek' annually receives heavy use (70 percent or more of the current year's growth); because heavy grazing reduces seed stock production by a factor of 30 to 50 times, and hence also seed production (Rodriguez and Welch 1986).

A summary word: 'Hobble Creek' big sagebrush is a highly preferred big sagebrush that can be established by several techniques and that can raise the level of energy, protein, phosphorus, and carotene in the diet of wintering domestic sheep and mule deer on those sites where it is adapted.

REFERENCES

Ammann, A. P.; Cowan, R. L.; Mothershead, C. L.; Baumgart, B. R. Dry matter and energy intake in relation to digestibility in white-tailed deer. Journal of Wildlife Management. 37: 195-201; 1973.

Davis, J. N.; Stevens, R. Comparison of production in 27 accessions of four sagebrush taxa. In: McArthur, E. D.; Welch, B. L., compilers. Proceedings—symposium on the biology of *Artemisia* and *Chrysothamnus*; 1984 July 9-13; Provo, UT. General Technical Report INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986: 336-341.

Elderkin, R. L. 1985. Personal Communications.

Frischknecht, N. C. Factors influencing brush invasion of crested wheatgrass range. Bulletin of the Ecological Society of America. 43: 53; 1962.

Hobbs, N. T.; Welch, B. L.; Remington, T. E. Effect of big sagebrush on *in vitro* digestion of grass cell wall. In: McArthur, E. D.; Welch, B. L., compilers. Proceedings—symposium on the biology of *Artemisia* and *Chrysothamnus*; 1984 July 9-13; Provo, UT. General Technical Report INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986: 186-189.

Hunter, R. B.; Wallace, A.; Romney, E. M. Fencing enhances shrub survival and growth for Mohave desert Nevada test site. Great Basin Naturalist Memoirs. 4: 212-215; 1980.

Jacobson, T. L. C.; Welch, B. L. Depth of planting 'Hobble Creek' sagebrush seed. 1986. Unpublished data on file at: Shrub Sciences Laboratory, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Provo, Utah.

Kelsey, R. G. Emergence, seedling growth, and crude terpenoid concentrations in a sagebrush garden. In: McArthur, E. D.; Welch, B. L., compilers. Proceedings—symposium on the biology of *Artemisia* and *Chrysothamnus*; 1984 July 9-13; Provo, UT. General Technical Report INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986: 358-365.

McArthur, E. D.; Plummer, A. P. Biogeography and management of native western shrubs: a case study, section *Tridentatae* of *Artemisia*. Great Basin Naturalist Memoirs. 2: 224-243; 1978.

McArthur, E. D.; Welch, B. L. Growth rate differences among big sagebrush (*Artemisia tridentata*) accessions and subspecies. Journal of Range Management. 35: 396-401; 1982.

Medin, D. E.; Anderson, A. E. Modeling the dynamics of a Colorado mule deer population. Wildlife Monographs. 68; 1979. 77 p.

Monsen, S. B.; McArthur, E. D. Factors influencing establishment of seeded broadleaf herbs and shrubs following fire. In: Sanders, K.; Durham, J.; [and others], eds. Rangeland fire effects: a symposium: Proceedings; 1984 November 27-29; Boise, ID. Boise, ID: U.S. Department of the Interior, Bureau of Land Management, Idaho State Office; 1985: 112-124.

Monsen, S. B.; Richardson, B. Z. Seeding shrubs with herbs on a semiarid mine site with and without topsoil. In: Tiedemann, A. R.; McArthur, E. D.; Stutz, H. C.; Stevens, R.; Johnson, K. R., compilers. Proceedings—symposium on the biology of *Atriplex* and related chenopods; 1983 May 2-6; Provo, UT. General Technical Report INT-172. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984: 298-305.

National Academy of Sciences. Nutrient requirement of sheep. Research Council Publication 5, 5th ed. Washington, DC; 1975. 72 p.

Nelson, D. L. Toward producing disease-free container-grown native wildland plants. In: Murphy, P. M., compiler. The challenge of producing native plants for the Intermountain area: Proceedings: Intermountain Nurseryman's Association 1983 conference; 1983 August 8-11; Las Vegas, NV. General Technical Report INT-168. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984: 32-38.

Nelson, D. L.; Krebill, R. G. A sagebrush wilt disease of unknown cause. Great Basin Naturalist. 41: 184-191; 1981.

Nelson, D. L.; Sturges, D. L. A snowmold disease of mountain big sagebrush. Phytopathology. [In press].

Pederson, J. C.; Welch, B. L. Effects of monoterpenoid exposure on ability of rumen inocula to digest a set of forages. Journal of Range Management. 35: 500-502; 1982.

Pederson, J. C.; Welch, B. L. Comparison of ponderosa pine as feed and nonfeed trees for Abert squirrels. Journal of Chemical Ecology. 11: 149-157; 1985.

Plummer, A. P.; Christensen, D. R.; Monsen, S. B. Restoring big game range in Utah. Publication No. 68-3. Salt Lake City, UT: Utah Division of Wildlife Resources; 1968. 183 p.

Plummer, A. P.; Monsen, S. B.; Stevens, R. Intermountain range plant names and symbols. General Technical Report INT-38. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 82 p.

Richardson, B. Z.; Monsen, S. B.; Bowers, D. M. Interseeding selected shrubs and herbs on mine disturbances in southeastern Idaho. In: McArthur, E. D.; Welch, B. L., compilers. Proceedings—symposium on the biology of *Artemisia* and *Chrysothamnus*; 1984 July 9-13; Provo, UT. General Technical Report INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986: 134-139.

Rodriguez, R. L.; Welch, B. L. 1986. Unpublished data on file at: Shrub Sciences Laboratory, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Provo, UT.

Stevens, R. Interseeding with a modified Sieco fireplow can result in increased seedling numbers. In: Proceedings, 39th vegetative rehabilitation and equipment workshop; 1985 February 10-11; Salt Lake City, UT. Missoula, MT: U.S. Department of Agriculture, Forest Service, Equipment Development Center; 1985: 22-27.

Stevens, R.; Jorgensen, K. R.; Davis, J. N. Viability of seed from thirty-two shrub and forb species through fifteen years of warehouse storage. Great Basin Naturalist. 41: 274-277; 1981.

Swenson, J. L., Jr.; Archer, W. M.; Donaldson, K. M.; Shiozak, J. J.; Broderick, B.; Woodward, L. Soil survey of Utah County, Utah—central part. Provo, UT: U.S. Department of Agriculture, Soil Conservation Service; 1972. 161 p.

Trickley, D. L.; Hall, D. T. Soil survey of Fairfield-Nephi area, Utah—parts of Juab, Sanpete, and Utah counties. Provo, UT: U.S. Department of Agriculture, Soil Conservation Service; 1984. 361 p. plus 130 maps.

U.S. Department of Agriculture, Soil Conservation Service. Gordon Creek Soil Survey Area. 1981. Unpublished data on file at: U.S. Department of Agriculture, Soil Conservation Service, Price, UT.

Utah State Engineer Office. Normal annual precipitation map. Salt Lake City, UT; 1931-1960.

Welch, B. L. Big sagebrush: nutrition, selection, and controversy. In: Johnson, K. L., ed. Proceedings, first Utah shrub ecology workshop; 1981; Ephraim, UT. Logan, UT: Utah State University; 1983: 21-33.

Welch, B. L.; Jacobson, T. L. C. Root development of 14 accessions of *Artemisia tridentata*. 1986. Unpublished data on file at: Shrub Sciences Laboratory, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Provo, UT.

Welch, B. L.; McArthur, E. D. Feasibility of improving big sagebrush (*Artemisia tridentata*) for use on mule deer winter ranges. In: Goodin, J. R.; Northington, D. K., eds. Proceedings, arid lands international conferences on plant resources; 1978; Lubbock, TX. Lubbock, TX: Texas Tech University, Center for Arid and SemiArid Land Studies; 1979a: 451-473.

Welch, B. L.; McArthur, E. D. Variation in winter levels of crude protein among *Artemisia tridentata* subspecies grown in a uniform garden. Journal of Range Management. 32: 467-469; 1979b.

Welch, B. L.; McArthur, E. D. Variation of monoterpenoid content among subspecies and accessions of *Artemisia tridentata* grown in a uniform garden. Journal of Range Management. 34: 380-384; 1981.

Welch, B. L.; McArthur, E. D. Growth rates of big sagebrush as influenced by accessions, sites, subspecies, and years. In: McArthur, E. D.; Welch, B. L., compilers. Proceedings—symposium on the biology of *Artemisia* and *Chrysothamnus*; 1984 July 9-13; Provo, UT. General Technical Report INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986a: 342-346.

Welch, B. L.; McArthur, E. D. Wintering mule deer preference for 21 accessions of big sagebrush. Great Basin Naturalist. 46: 1986b. [In press].

Welch, B. L.; McArthur, E. D.; Davis, J. N. Differential preference of wintering mule deer for accessions of big sagebrush and for black sagebrush. Journal of Range Management. 34: 409-411; 1981.

Welch, B. L.; McArthur, E. D.; Davis, J. N. Mule deer preference and monoterpenoids (essential oils). Journal of Range Management. 36: 485-487; 1983.

Welch, B. L.; McArthur, E. D.; Rodriguez, R. L. Wintering domestic sheep preference for 21 accessions of big sagebrush. Journal of Range Management. [In press].

Welch, B. L.; Pederson, J. C. *In vitro* digestibility among accessions of big sagebrush by wild mule deer and its relationship to monoterpenoid content. Journal of Range Management. 34: 497-500; 1981.

White, S. M.; Flinders, J. T.; Welch, B. L. Preference of pygmy rabbits (*Brachylagus idahoensis*) for various populations of big sagebrush (*Artemisia tridentata*). Journal of Range Management. 35: 724-726; 1982.

Winward, A. H. Using sagebrush ecology in wildland management. In: Johnson, K. L., ed. Proceedings, first Utah shrub ecology workshop; 1981; Logan, UT. Logan, UT: Utah State University; 1983: 15-19.

Young, J. A.; Evans, R. A. Seedling establishment of five sources of big sagebrush in reciprocal gardens. In: McArthur, E. D.; Welch, B. L., compilers. Proceedings—symposium on the biology of *Artemisia* and *Chrysothamnus*; 1984 July 9-13; Provo, UT. General Technical Report INT-200. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986: 370-374.

Welch, Bruce L.; McArthur, E. Durant; Nelson, David L.; Pederson, Jordan C.; Davis, James N. 'Hobble Creek'— a superior selection of low-elevation mountain big sagebrush. Research Paper INT-370. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 10 p.

About 15 years of research and evaluation resulted in identification of a superior selection of big sagebrush (*Artemisia tridentata*) for use on mule deer and domestic sheep winter ranges. This selection can raise the level of energy, protein, phosphorus, and carotene in the diet of wintering sheep and mule deer. A. Perry Plummer discovered the plant in 1968 at the mouth of Hobble Creek drainage just east of Springville, UT. 'Hobble Creek' is a low-elevation mountain big sagebrush. We describe the need, nutrient profile, areas where it can be grown, disease relations, and establishment procedures for the selection.

KEYWORDS: winter range, nutritive value, establishment, revegetation, *Artemisia tridentata*, mule deer, domestic sheep

---

PESTICIDE PRECAUTIONARY STATEMENT

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

United States
Department of
Agriculture

Forest Service

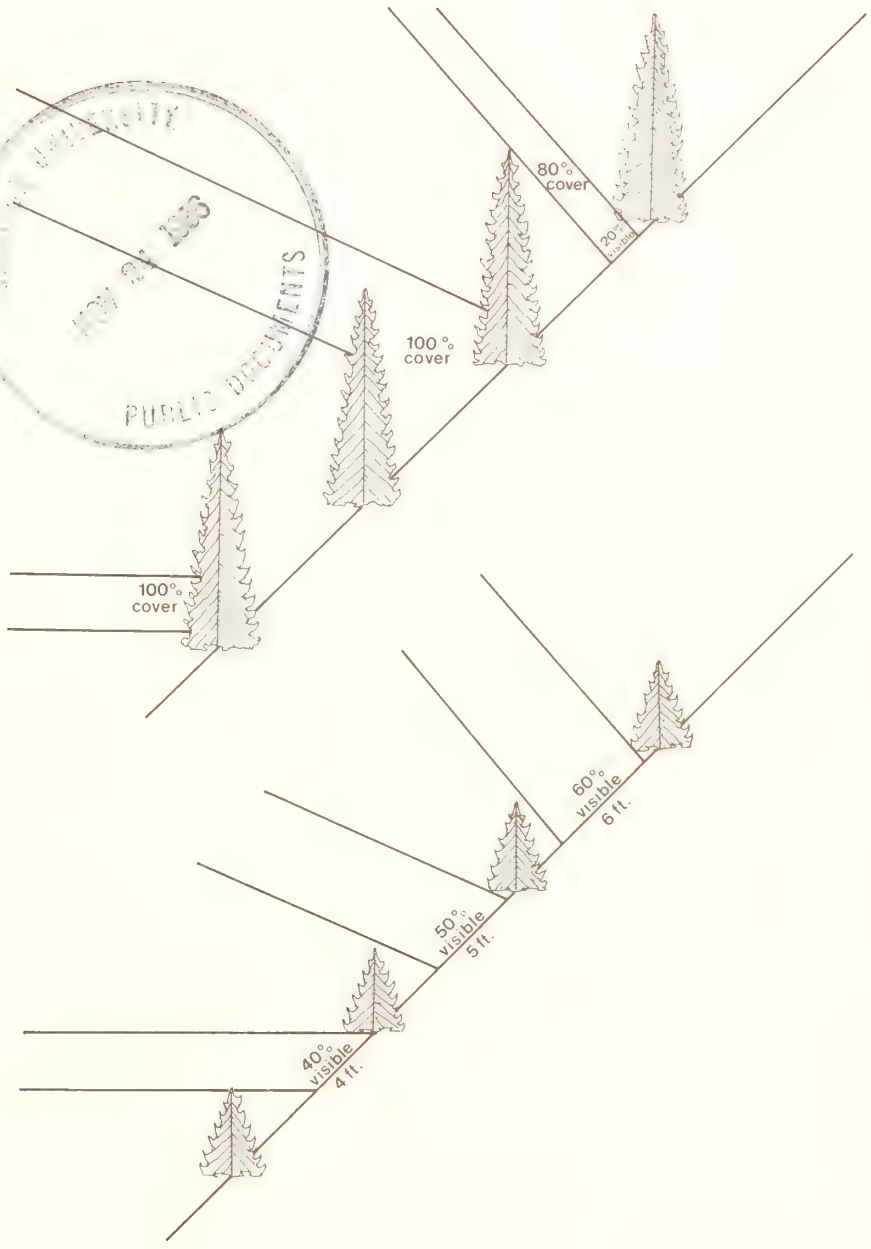
**Intermountain
Research Station**

Research Paper
INT-371

October 1986

The Influence of Viewing Angle on Elk Hiding Cover in Young Timber Stands

Jodie E. Canfield
L. Jack Lyon
J. Michael Hillis



PUBLIC DOCUMENTS

RESEARCH SUMMARY

Young timber stands, even when providing 100 percent visual concealment for elk when viewed on a horizontal plane, may provide 50 percent or less cover when viewed from an opposing slope at an elevated viewing angle. The higher the viewing angle, the greater the relative cover loss. In a simple linear model, viewing angle explained 52 percent of the variation in hiding cover values. Slightly more variation was accounted for when the data were stratified by tree height. On the average, for a 10-degree elevation in viewing angle, hiding cover decreased by 10 percent. The cover loss relationship was most pronounced in stands with the steepest topography, the shortest trees, and the lowest tree and shrub densities.

THE AUTHORS

JODIE E. CANFIELD has been associated with the Lolo National Forest in a temporary position testing Forest Plan assumptions about elk habitat and vegetative relationships. She attended Oregon State University and received B.S. and M.S. degrees in wildlife management from Montana State University. Her M.S. degree thesis, completed in 1984, reported the effects of a 500-kv transmission line on wintering elk populations.

L. JACK LYON, wildlife research biologist, has been leader since 1962 of the research work unit devoted to ecology and management of wildlife habitat. This unit is headquartered at the Intermountain Research Station, Forestry Sciences Laboratory, Missoula, MT. Dr. Lyon holds B.S. and M.S. degrees in wildlife management from Colorado State University and a Ph.D. degree from the University of Michigan.

J. MICHAEL HILLIS, wildlife biologist, has been assigned to the Lolo National Forest in Missoula, MT, since 1977. He received a B.S. degree in wildlife management from Oregon State University in 1970. From 1972 to 1974 he worked as a wildlife biologist with the Siskiyou National Forest in western Oregon, and from 1974 to 1977 he held the same position with the Umatilla National Forest in northeastern Oregon.

ACKNOWLEDGMENTS

The following people are recognized for their contributions to this study: Greg Munther, Lolo National Forest, suggested the original study idea; Mike Paterni, Deerlodge National Forest, helped to procure funding and work out the study design. Field assistance was provided by John Sullivan. Our sincere thanks also to the Lolo and Deerlodge District Offices for their help in obtaining information on study stands.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

The Influence of Viewing Angle on Elk Hiding Cover in Young Timber Stands

Jodie E. Canfield
L. Jack Lyon
J. Michael Hillis

INTRODUCTION

Habitat effectiveness for elk is closely tied to the quality of security cover (Lyon and others 1985). Because forested lands in western Montana have high values for both timber and elk, it is desirable to schedule timber harvest so that adequate amounts of elk hiding cover are continually available.

Land managers have assumed that cutover stands begin to provide hiding cover when conifers are 6 to 8 ft in height. Well-stocked, regenerating stands of this height will provide hiding cover about 15 years after harvest. The National Forests in western Montana recognize the need for elk hiding cover in timber harvest areas with constraints or policies intended to prevent the removal of cover stands adjacent to clearcuts until the clearcut has trees of this height. Evaluations are based on data from timber and wildlife habitat inventories or aerial photos and do not normally consider hiding cover values from observation points outside the stand.

Steep dissected topography, common in the Northern Rockies, often allows an observer to stand on slopes opposing cutover areas and look down into young stands of conifers. Our initial observations suggested that hiding cover values are dramatically compromised by elevated viewing angles. Consequently, existing evaluation methods may overestimate elk hiding cover values.

This study was conducted on the Lolo and Deerlodge National Forests of Montana as a means of testing the hypothesis that elk hiding cover values in young timber stands decrease proportionately as viewing angle increases from the horizontal.

The specific objectives of this study were:

1. To determine the relative loss in hiding cover values associated with changing the angle from which a stand is viewed.
2. To develop a model for describing any such losses in hiding cover.
3. To provide guidelines for improving elk/timber management strategies in forested areas with dissected topography.

Fieldwork was started in June 1985 and completed the following September. Funding and logistical support were provided by the Lolo and Deerlodge National Forests and the Intermountain Research Station.

STUDY SITE AND METHODS

Study sites were selected on the Lolo and Deerlodge National Forests in areas with dissected topography. Within these areas, sample stands were selected with trees between 5 and 25 ft tall and with an opposing slope providing an unobstructed view into the sample stand. Information on stand age and treatment was available from Forest Service timber inventory records.

Within a representative portion of a stand, a 250-ft transect was laid out across the slope. Transects consisted of five tangential circular plots, each with radius of 25 ft. Slope, aspect, elevation, and habitat type (Pfister and others 1977) were recorded for each transect. Within each circular plot, basal area, tree density, shrub density, canopy cover, tree crown height, and tree species were recorded.

At each plot center, a cover board (Nudds 1977) was evaluated by an observer 50 ft away, at the next plot center. The observer estimated the proportion of each of four equally spaced panels covered by vegetation, assigning a 0 for no cover, and up to a 5 for complete cover.

The influence of viewing angle on hiding cover was quantified using a modification of a method developed by Mike Hillis on the Lolo National Forest. A "target" individual moved randomly along the transect while an observer on the opposite slope recorded the percentage of 20 observations, taken at 5-second intervals, that the target was not visible as a human torso. This was defined as the "Hillis hiding cover." Observation points were typically located in the valley and progressively uphill on the slope opposite the study stand. We recorded two to five replications per stand, with successive sampling points 10 or more degrees of slope apart. The slope within the stand, on line of sight to the observer, plus the angle from the observer to the target, was defined as the viewing angle (fig. 1).

In most situations, as the viewing angle increased, distance between the observer and the target also increased. There was no evidence in our data that distances less than 1,000 ft biased the observer's ability to distinguish the target as human torso.

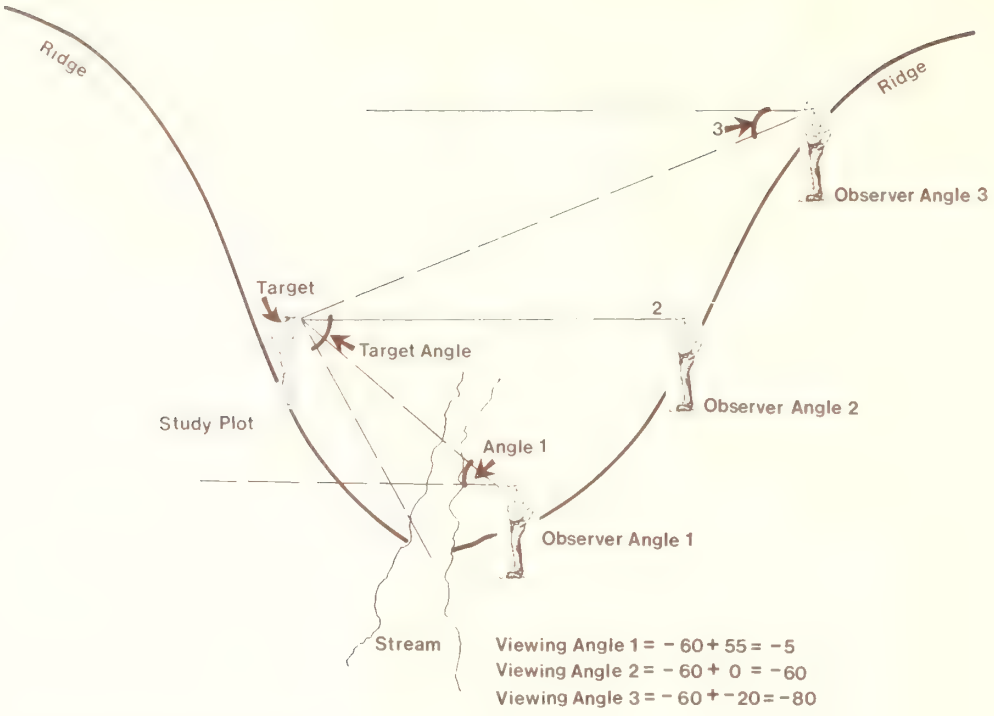


Figure 1—Hillis hiding cover estimation by observer to target in study plot. Hiding cover is the percentage of 20 observations that the target is not visible for a given viewing angle.

ANALYSIS

Raw data from 147 stands were transcribed and summarized to produce averages of measured stand parameters for each transect. Analysis was keyed to predicting the relative loss in hiding cover depending on the angle from which a stand is viewed.

Within each study stand, the regression of Hillis hiding cover values on viewing angles was calculated. The resulting Y-intercept was taken as the projected Hillis cover value of the stand with the viewing angle zero. Hillis cover values were then subtracted from the projected cover value (Y-intercept) to predict cover loss values expressed as units of percentage points.

The basic relationship, regression of cover loss on viewing angle, was assumed to be related to some or all of the vegetative factors measured. This assumption was tested by stratifying the data along a gradient of values for each vegetative factor and fitting a line or a curve to each level of stratification. In addition, discriminate analysis was used to identify those vegetative factors most useful in separating stands classified by the slope of their individual linear regressions.

RESULTS

The average number of Hillis hiding cover measurements in 144 stands was 3.67. Three stands with only one observation were excluded from the analyses. Table 1 lists the means, standard deviations, and ranges of several descriptive variables recorded for study stands.

Table 1—Means standard deviations (s.d.), and ranges for selected variables recorded for study stands (N = 144)

Variable	Mean	s.d.	Range
Basal area	14.2	17.3	0-54
Trees/acre	497	600	84-2,458
Shrubs/acre	167	298	0-2,649
Canopy cover percentage	16.9	21.3	0-69
Tree height (ft)	12.5	13.2	5-27
Slope percentage	34	16	3-63
Elevation (ft)	5,268	663	4,040-7,280
Age (years)	19	20	6-35

For each study stand, the Hillis hiding cover values (Y-axis) were plotted against their corresponding viewing angle (X-axis). The slope and Y-intercept values from the linear regressions ranged from 0 to 2.48 and 38 to 100, respectively. The average slope was 0.9617, and the average Y-intercept was 79.

Stands were placed into three categories based on rate of change in hiding cover relative to changes in viewing angle. Table 2 presents the means of vegetative measurements in each category.

Table 2 shows that, on the average, stands with the least change in hiding cover relative to change in viewing angle had the highest values for all vegetative factors except tree density.

Table 2—Mean values for some vegetative measurements for three groups of stands based on the slope of individual regressions

Slope category	Basal area	Trees/acre	Shrubs/acre	Canopy cover	Tree height
	Acres			*Percent*	*Feet*
.00-0.74	16.9	522	250	24	13.9
.75-1.19	12.8	416	150	16	12.9
.20-2.48	12.6	544	122	10	10.4

Using basal area, tree density, shrub density, canopy cover, and tree height as independent variables, discriminate analysis correctly classified 55 percent of the study stands into the proper slope category. Canopy cover and tree height had the highest canonical coefficients. Because tree height is more easily measured than canopy cover, it was selected for use in further analyses.

An attempt was made to detect correlations between stand projected cover values (Y-intercept) and stand vegetative factors. No highly significant correlations were found. Hiding cover values within the stand, measured with a cover board, were only moderately correlated with the stand Y-intercepts.

Because each stand produced between two and five estimates of Hillis hiding cover, a total of 525 (x,y) pairs were included in the overall regression of cover loss on viewing angle.

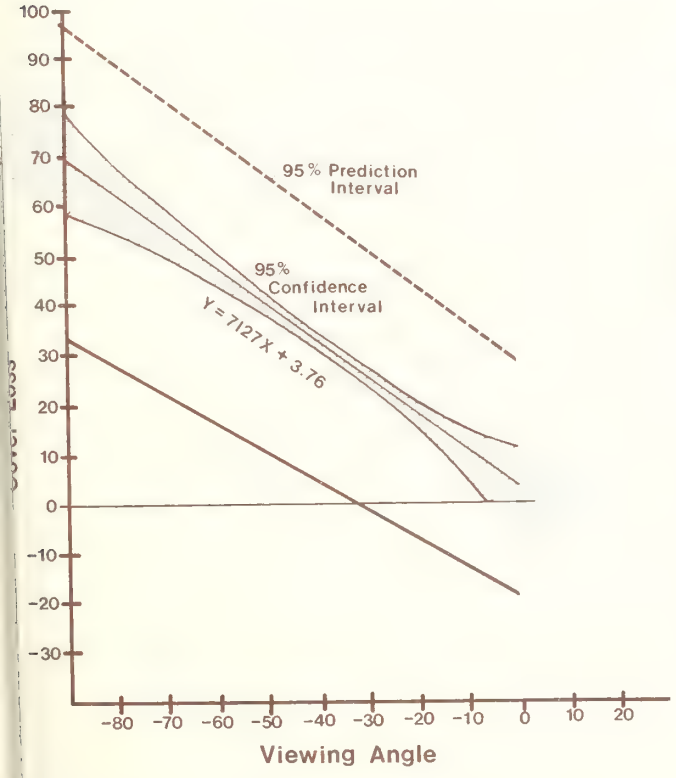
The overall linear regression is graphed in figure 2 for viewing angles between 0 and 75 degrees. A curvilinear model fitted to the data improved the r value from the linear r, but not significantly. The standard error of the estimate was 13.88. Values for slope, Y-intercept, and the correlation coefficient, and their 95 percent confidence intervals are given in table 3.

We assumed that the variance in the overall regression was due in part to some vegetative factor. Only linear stratifications on tree height and canopy cover proved significantly different from a single overall equation.

The three equations based on groups of tree height are graphed in figure 3. Values for the regression parameters and the standard error of the regressions ($S_{y.x}$) are given in table 4. Curvilinear functions improved the correlation coefficients an average of 13 percent. This was not a significant improvement.

Table 3—Values and confidence intervals for the regression of cover loss on viewing angle (N = 525), Y = 3.76 + 0.713X

Factor	Estimated value	95% confidence interval
Slope (b)	0.7127	0.6539-0.7715
Y-intercept (a)	3.76	2.58-4.94
Correlation (r)	.72	0.68-0.76



gure 2—Comprehensive linear model (N = 525). over loss predicted from viewing angle.

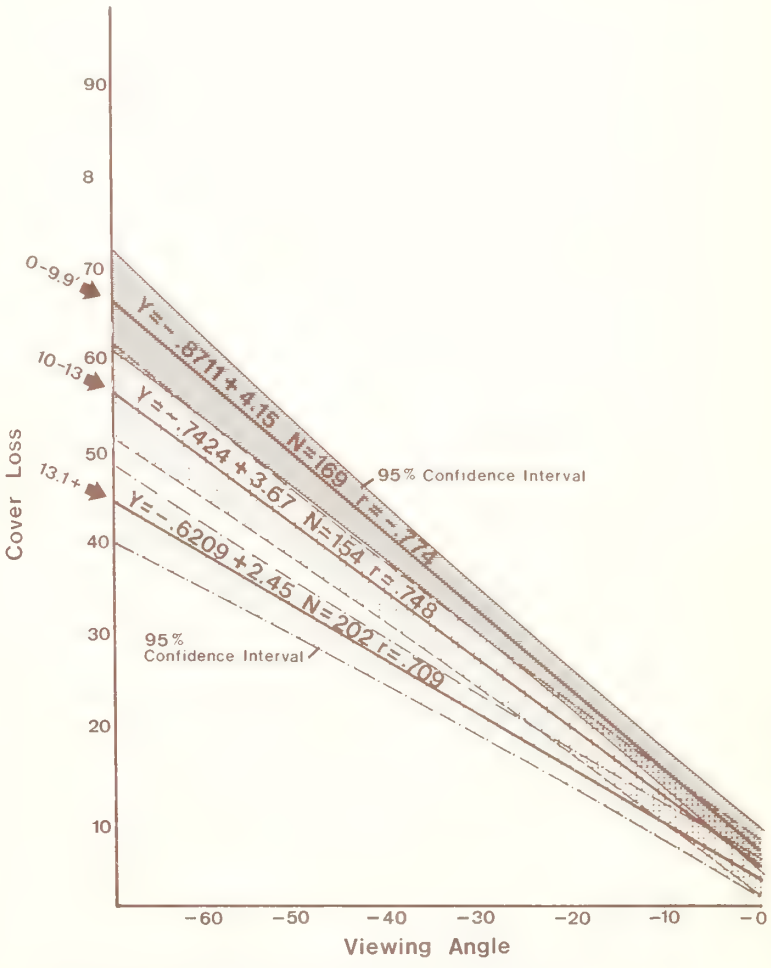


Figure 3—Linear models and 95 percent confidence intervals for three classes of tree height. Cover loss predicted from viewing angle.

Table 4—Standard error of the estimates, regression parameter values, and 95 percent confidence intervals for three linear models based on tree height

Height group	N	$S_{y.x}$	Slope	Mean Y	Mean X	r
5-9.9	169	13.7	0.8711 ± 0.118	24.74 ± 2.1	−23.64	0.774 ± 0.06
10-13	154	14.3	.7424 ± .118	24.65 ± 2.3	−28.26	.748 ± .08
13.1-21	202	12.2	.6209 ± .078	20.89 ± 1.7	−29.70	.709 ± .06

Statistical tests showed the short tree and tall tree models to be significantly different. Although neither the slope nor the Y-intercept of the medium height model were significantly different from the short tree model, there was significantly less unexplained variance using two separate models over a single combined model. The regression line for medium height trees was parallel to the line for tall trees.

In figure 3, the regression lines diverge as the viewing angle increases. The mean values of Y predicted from each of the three linear equations were significantly different for viewing angles greater than 10 degrees.

All tree heights in the sample, from 5 to 21 ft (there was one stand with trees 27 ft tall), showed a hiding cover loss with increasing viewing angle, although the rate of hiding cover loss relative to viewing angle declined as tree height increased. The threshold of tree height after which the relationship does not exist is greater than 21 ft. From field observations, we estimate this height to be 25 to 30 ft.

We detected no significant correlation between tree height in a stand and the age or treatment of the stand, even when stands were grouped by habitat type. However, the majority of the stands were clearcuts between 15 and 25 years old.

DISCUSSION

The stands included in this study were quite diverse. They included samples from the relatively open, rolling hill lodgepole stands of the Deerlodge National Forest, to the steep, closed Douglas-fir and subalpine fir stands typical of the Lolo National Forest. Therefore, the results should be applicable to all situations in which timber is harvested in areas with some topographic relief.

Only a few documented methods exist for quantifying hiding cover for wildlife. For elk, cover that conceals 90 percent of an animal at a distance less than 200 ft is considered hiding cover (Thomas and others 1976). We used two methods for measuring hiding cover in this study—a cover board for within-stand evaluation and the modified Hillis method for evaluating cover from outside the stand. Cover board measurements were only moderately correlated with Hillis values at viewing angles near zero. Therefore, the Hillis method is relevant only in the sense that a measurement of 100 percent Hillis cover at one angle, and a reading of 85 percent at a higher angle, constitute a cover loss of 15 percentage points.

We had assumed that cover loss was a function of the vegetative factors we chose to measure. None of the analyses confirmed this assumption. The distribution of vegetation and its vertical structure may also be important but would be difficult to measure or quantify. Shrub height may also be important. Furthermore, different combinations of vegetative features can be equally effective at providing cover. For example, a stand with a few big trees and abundant shrubs may provide the same cover as a stand with dense short trees and no shrubs. Overall, as would be expected, the cover loss/angle relationship was least pronounced in stands with thick boles, tall trees, and dense shrubs. Although many other factors are involved, tree height appears to be the variable most responsible for buffering cover loss from steep viewing angles. That is, as tree height increases, there is a trigonometric layering effect that obstructs view into the stand even at elevated viewing angles (see cover).

Although slightly more variation was explained using curvilinear functions, the linear models were selected for simplicity. For angles between 0 and 50 degrees, the regression was steep and linear. At angles greater than 50 degrees, cover loss leveled. There seemed to be a threshold angle for each stand beyond which no further changes in cover could be detected. Only in very open stands did hiding cover decline to zero.

Changes in viewing angle (one variable) explained 52 percent of the variation in cover loss in the combined linear model, 60 percent in the short tree model, 56 percent for trees 10 to 13 ft tall, and 50 percent for trees 14 to 21 ft tall.

Given clearcuts with young trees, the cover loss/angle relationship will be pronounced in areas of steep topography and in narrow valleys. In these situations, observation points are typically outside of a stand. Conversely, on relatively level ground, and in wide canyons where distance to the opposing slope is greater than 0.25 mile, it is unlikely that this relationship will be important.

Although it was not addressed in this study, stands dominated by western larch (*Larix occidentalis*) may be particularly vulnerable to hiding cover loss at elevated viewing angles in the fall after needle drop. This is significant in that it is concurrent with heavy recreational use of forest roads by hunters.

Clearcuts may provide foraging areas for elk in heavily timbered areas. However, the use of seral stages for foraging is often tempered by the quality of security cover in the adjacent forest (Irwin and Peek 1983; Lyon and Jensen 1980). Elk tend to underutilize habitat near forest roads that are open to vehicular traffic. This avoidance is especially pronounced in areas of poor security cover and during the big-game hunting season (Irwin and Peek 1983; Lyon 1979). Therefore, the security of elk habitat in areas where timber is harvested depends on the spacial arrangement of cutting units and the management of roads.

MANAGEMENT RECOMMENDATIONS

The cover loss phenomenon can be minimized and hiding cover for wildlife can be continually available if resource planners implement the following recommendations in areas with steep, timbered topography:

1. Stagger timber harvest units so that opposing slopes and adjacent units are never cut concurrently. This will ensure that a clearcut cannot be viewed from an opposing slope and that security cover is available on the edges of a cut.
2. In relatively steep topographic situations where a young timber stand can be viewed from an opposing slope, delay reentry until trees are 25 to 30 ft tall.
3. Avoid, when possible, building roads across an uncut slope that opposes a cutover unit. These roads provide a viewing angle into cut stands. The higher on a slope a road is built, the greater the potential hiding cover loss in the opposing stand.
4. Implement road closures in areas of steep dissected topography where timber harvest has been extensive. Close existing roads where they provide access across an uncut slope that opposes a cut slope. Road closures are especially critical during the fall hunting season.

The impact of these recommendations on timber harvest yield and economics is considered low. Initial sampling on the Lolo Forest has indicated that viewing angle relationships play a significant role on only about 20 percent of the lands allocated for timber harvest. Consequently, these recommendations can be viewed as a valuable management tool for achieving desired elk summer range with minimal impacts on the timber resource.

To ensure the continued enjoyment of the many resources on our National Forests, the interactions of those resources and their uses must be considered. Where elk habitat exists on forested public land, it is essential that security cover be continually available. This study reveals that young timber stands are not effective at providing elk hiding cover where topography is dissected and the observation point is outside and above the stand. The hiding cover loss associated with elevated viewing angles can be minimized with careful planning and cooperation between timber and wildlife managers.

REFERENCES

Irwin, L. L.; Peek, J. M. Elk habitat use relative to forest succession in Idaho. Journal of Wildlife Management. 47: 664-672; 1983.

Lyon, L. J. Habitat effectiveness for elk as influenced by roads and cover. Journal of Forestry. 77: 658-660; 1979.

Lyon, L. J. Road density models describing habitat effectiveness for elk. Journal of Forestry. 81: 592-595; 1983.

Lyon, L. J.; Jensen, C. E. Management implications of elk and deer use of clearcuts in Montana. Journal of Wildlife Management. 44: 352-362; 1980.

Lyon, L. J.; Lonner, T. N.; Weigand, J. P.; Marcum, C. L.; Edge, D. W.; Jones, J. D.; McCleerey, D. W.; Hicks, L. L. Coordinating elk and timber management. Final report of the Montana cooperative elk-logging study, 1970-1985. Bozeman, MT: Montana Department of Fish, Wildlife and Parks; 1985. 53 p.

Nudds, T. D. Quantifying the vegetative structure of wildlife cover. Wildlife Society Bulletin. 5(3): 113-117; 1977.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, B. C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 174 p.

Thomas, J. W.; Miller, R. J.; Black, J. E. Rodiek; Maser, C. Guidelines for maintaining and enhancing wildlife habitat in forest management in the Blue Mountains of Oregon and Washington. Transactions of the North American Wildlife and Natural Resources Conference. 41: 452-476; 1976.

Canfield, Jodie E.; Lyon, L. Jack; Hillis, J. Michael. The influence of viewing angle on elk hiding cover in young timber stands. Research Paper INT-371. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 5 p.

Young timber stands that provide hiding cover for elk when viewed on a horizontal plane provide far less security when viewed from an opposing slope at an elevated viewing angle. On the average, for a 10-degree elevation in viewing angle, hiding cover decreases by 10 percent.

KEYWORDS: hiding cover, viewing angle, elk

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research
Paper INT-372

November 1986

Pinyon-Juniper Site Quality and Volume Growth Equations for Nevada

David C. Chojnacky

THE AUTHOR

DAVID C. CHOJNACKY is a research forester in the Forest Survey unit, Intermountain Research Station, Ogden, UT. He holds a B.S. degree in mathematics from the University of Idaho, Moscow, and an M.S. degree in watershed management from the University of Arizona, Tucson, and Ph.D. degree in forest biometry from Colorado State University, Fort Collins. He has been with the Forest Service since 1979. Before coming to Ogden, he worked for the Forest Research Laboratory at Oregon State University, Corvallis.

RESEARCH SUMMARY

Site quality and volume growth equations were developed for Nevada's pinyon-juniper (P-J) woodlands. A site index equation was built from a relationship between tree height and diameter. Two types of stand volume growth equations were constructed. Periodic annual volume growth was predicted from total crown volume, juniper crown cover, basal area, and quadratic mean diameter data. The other type of growth, long-term average annual yield from fully stocked stands, was predicted from site index.

ACKNOWLEDGMENTS

Data for this study came from lands managed by the U.S. Department of the Interior, Bureau of Land Management (BLM). Special thanks to Dave Schmidt and Steve Langdon, former temporary employees of the Intermountain Research Station, who felled and measured the study trees.

Cover Photo: Pinyon-juniper on the Elko, NV, BLM District, by Skip Ritter

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Pinyon-Juniper Site Quality and Volume Growth Equations for Nevada

David C. Chojnacky

INTRODUCTION

In recent years, land managers have become increasingly aware of the potential value of the 42 million acres of pinyon-juniper (P-J) woodlands in the Rocky Mountain States. Inventories of P-J recently were done for the first time in Nevada, Idaho, Utah, Colorado, New Mexico, and Arizona. However, these inventories were conducted without procedures to estimate site quality and wood volume growth because adequate methods were unavailable. As an attempt to fill this information void, this study was initiated using a more intensively measured subsample of plots from the Nevada P-J inventory. The study was an exploratory effort to develop site quality and stand growth equations for use in P-J inventories.

PREVIOUS WORK

Two ideas about site quality in P-J woodlands have been proposed. The first is structural tree support theory. McMahon (1973) put forward a structural support theory, finding tree height proportional to basal trunk diameter raised to the two-thirds power. Tausch (1980) generalized McMahon's finding in a simple plant dimension model and proposed using the proportionality constant as a site quality measure:

$$Y = a \cdot X^b \qquad (1)$$

where

a = the proportionality constant or site quality measure

Y,X = dimensions of plant parts

b = a theoretical constant, unaffected by site quality and plant succession.

For singleleaf pinyon in Utah and Nevada, Tausch (1980, p. 127) found basal diameter and crown volume to be promising plant dimensions to use for X and Y in equation 1.

Daniel and others (1966) used a site quality measurement strategy somewhat related to the structural support theory. They developed pinyon site index curves based on the relationship between height and basal diameter dimensions on dominant trees.

The second idea of P-J site quality determination involved the growth of P-J woodlands. Meeuwig and Cooper (1981) defined a P-J site quality index as the total basal area growth of all trees per acre, per decade, in fully stocked stands. They defined as fully stocked those stands with undergrowth shrub and grass vegetation less than 10 percent of the total plant cover (trees, shrubs, and grasses). Because undergrowth is more than 10 percent of the total plant cover in many P-J stands, Meeuwig and Cooper developed a basal area growth prediction equation from topographic and soil measurements. However, this equation explained only 42 percent of the variation (R^2 = 0.42) in their data.

Another site index involving growth was Howell's (1940) use of average P-J basal area. Howell postulated that total basal area of a stand is an indicator of site quality when all trees average 5 inches at basal diameter. He modeled this by multiplying basal area by five times the reciprocal of average diameter when stands had an average basal diameter other than 5 inches.

Volume growth for individual P-J trees was examined by Meeuwig and Budy (1981). They developed growth equations from diameter, height, crown, and radial diameter growth measurements. Meeuwig and Cooper (1981) constructed a potential stand growth equation for fully stocked stands using basal area growth as the input variable.

Previous site quality and growth work has not been applied to P-J inventories because the results either were presented in a nonusable form or required impractical field measurements. For example, the site index graphs reported by Howell and Daniel and others were not accompanied by equations. Tausch's ideas have not yet been tested against data. And the equations constructed by Meeuwig and coauthors required 10-year diameter growth measurements for all or most trees sampled in an inventory. Because P-J diameter growth is best measured from cores or cross-sections under magnification in a laboratory, measuring diameter growth in large P-J inventories is considered too costly.

In this study, three relationships were modeled to aid site quality and stand growth estimation in P-J inventories:

1. Site index was modeled from the proportionality between tree diameter and height.
2. Periodic annual volume growth (PAI) was modeled from easily obtained P-J inventory variables.
3. Potential long-term average yield (PLAY) of fully stocked stands was modeled from site index.

PAI was defined in the usual way (Husch and others 1982, p. 276) as average annual volume growth of the last 10 years for all trees in a stand combined into a per-acre expression. PLAY was a descriptor devised for this study (only for fully stocked stands) to describe individual tree volume divided by tree age for all trees in a stand combined into a per-acre expression. PLAY was used in place

of yield capability (Brickell 1970) to describe potential yield of P-J woodlands. Yield capability as defined by the Forest Service (Forest Survey) is the mean annual volume growth increment (MAI) attainable in fully stocked natural stands at the age of maximum MAI. An alternative to yield capability was needed because Meeuwig and Cooper (1981) found no indication of basal area growth (which is strongly related to volume growth) approaching some maximum value for fully stocked stands up to 240 years old—the oldest stands they located in Nevada.

DATA COLLECTION

Singleleaf pinyon (*Pinus monophylla* Torr. & Frém.) and Utah juniper (*Juniperus osteosperma* [Torr.] Little) trees were sampled from 44 study plots in Nevada (fig. 1). Field measurements for this study were taken as a secondary task of a Forest Service quality control crew that was checking a U.S. Department of the Interior, Bureau of Land Management (BLM) woodland inventory. This arrangement required a flexible sample design to coordinate study plots with BLM inventory plots. Another constraint was the rigid time schedule (one plot per day) required by the Forest Service. To accommodate these constraints, two to four line-intersect transects (Meeuwig and Budy 1981) were superimposed on each 1/10-acre BLM plot included in this study. The transects, 77 feet in length, were laid out from a common origin 90 degrees apart. Trees selected on each transect were measured for diameter near ground line at 6-inch stump height (DSH), 10-year radial growth (two to four cores per tree measured under magnification), total height, crown volume form (coded for an ellipse, cone, sphere, or paraboloid), height to the base of the crown (HBC), maximum crown diameter (CRMX), crown diameter perpendicular to the maximum (CRMN), and numbers of basal stems. Only trees with at least one stem 3 inches DSH or larger were measured. For trees that forked at point of diameter measurement, an equivalent diameter was computed (Meeuwig and Budy 1981):

$$ED = \sqrt{D_1^2 + D_2^2 + D_3^2 + \ldots + D_n^2} \qquad (2)$$

where

ED = equivalent diameter

D = diameter of an individual stem

n = number of stems.

Trees selected along the last 40 feet of each transect (about half the trees sampled) were cut down to obtain age and volume. Total age was measured under magnification from a cross-section taken at 6-inch stump height. An outside bark volume was calculated from Newton's log formula (Husch and others 1982, p. 101) for all wood segments in a tree larger than 1.5 inches in diameter. Understory cover was obtained along the same transects used for tree measurements. Shrub and bunchgrass cover was measured by the line intercept method (Canfield 1941). Other grass and forb cover was measured by ocular estimation within two 1- by 5-foot quadrats spaced 20 feet apart along each transect. (More detailed instructions for the field measurements are documented in the 1980 Nevada Forest Survey field procedures, USDA-FS 1980.)

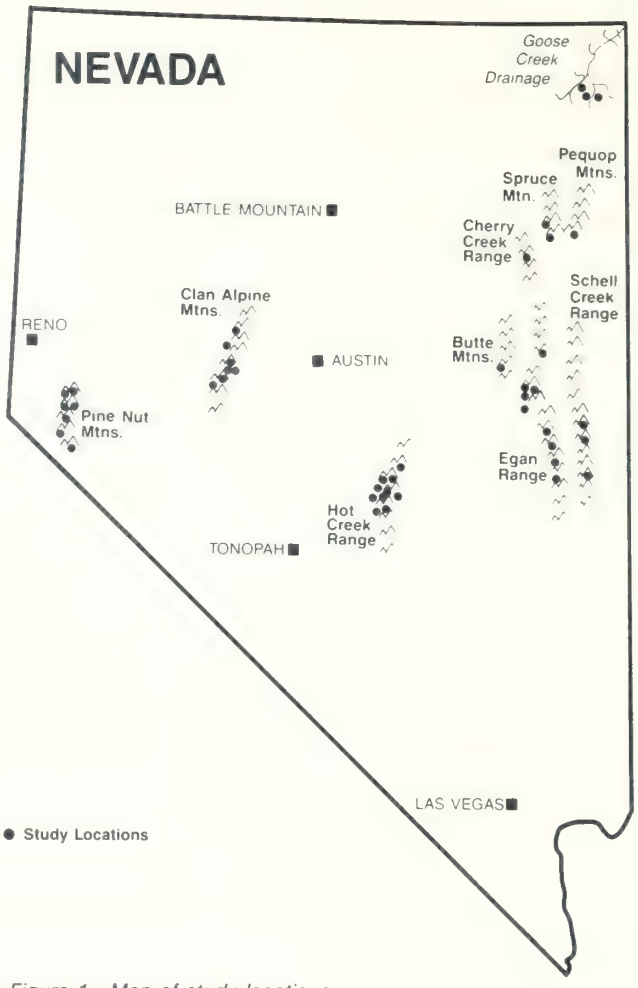


Figure 1—Map of study locations.

Besides field measurements, age and volume equations were needed to compute PAI and PLAY. By using the trees cut down for each study plot, prediction equations were developed for determining ages for those trees not aged, and for determining volume growth (eqs. 14 and 15 in the appendix). Two types of volume growth, PLAY and PAI, were computed for each tree. PLAY was computed by dividing a tree's estimated volume by its age. PAI was calculated from the difference between a tree's present volume and its past volume. Past volume for each tree was computed from the volume equation by back-dating DSH using 10-year radial growth measurements. This then was subtracted from the tree's present volume and the result divided by 10 to obtain PAI. All volume estimates for PLAY and PAI were determined from equations used for every tree (including those measured for volume) to maintain consistency between present and past volume estimation.

Site trees were identified for each study plot by computer selection. About four trees per plot having the largest height to DSH ratios were chosen.

The individual tree data were expanded to per-acre estimates for each study plot using Meeuwig and Budy's (1981) method. Canfield's (1941) method was used to expand the understory data. A summary of data and within-plot sampling variation for each study plot is given in table 1.

Table 1—Summary of the data for each of the 44 study plots

BLM District	Geographic area	Volume	PAI	Crown volume	Basal area	Quadratic mean DSH	Trees	Median stand age	Total tree cover	Shrub and grass cover	Trees sampled	Transects sampled	C.V. for basal area	C.V. for trees per acre
		Ft^3/acre	Ft^3/acre/yr	1,000 ft^3/acre	Ft^2/acre	Inches	No./acre	Years	Percent		No.		Percent	
Battle Mountain	Hot Creek Range	687	8	71	71	9.5	144	132	25	2	10	4	93	89
		761	13	100	107	8.7	260	95	38	8	8	2	78	76
		344	4	26	55	7.9	161	117	16	8	4	2	62	35
		718	6	64	69	13.2	73	173	22	6	6	3	96	93
		1,127	26	188	126	7.6	403	86	59	0	12	2	31	27
		265	4	34	37	13.1	40	207	12	13	4	4	167	172
		638	5	55	170	13.2	180	190	28	8	11	4	99	78
		498	7	110	71	8.8	169	82	37	8	12	4	65	69
		319	4	37	38	9.4	80	170	14	34	6	3	101	101
		541	5	77	133	8.3	357	160	36	0	16	3	17	35
Carson City	Clan Alpine Mountains	514	2	28	79	13.7	77	187	16	3	4	3	110	94
		286	9	90	40	5.4	250	46	33	14	7	2	109	89
		493	5	58	72	9.8	138	96	23	1	9	4	109	128
		1,308	11	150	113	9.1	250	163	42	15	12	3	96	85
		1,845	8	145	169	14.8	142	180	39	46	9	3	96	66
		1,701	15	182	141	10.6	228	132	43	12	8	2	82	74
		1,076	13	147	105	6.9	404	112	42	2	10	2	109	76
	Pine Nut Mountains	1,236	17	219	111	8.9	258	75	60	6	13	3	44	110
		1,119	11	198	84	13.7	81	99	47	8	10	4	121	101
		861	12	143	61	8.1	171	70	41	10	11	4	48	116
		1,162	18	214	81	11.6	110	121	51	2	12	4	73	71
		1,245	22	230	129	8.4	334	71	68	1	12	2	52	51
		279	4	74	50	9.5	102	89	30	11	9	4	121	62
		546	11	132	45	9.0	103	68	35	18	10	4	91	96
Elko	Cherry Creek Range	804	7	68	192	10.9	299	227	34	13	16	4	83	107
	Goose Creek Drainage	796	6	118	134	7.9	399	137	44	21	10	2	46	46
		1,309	8	170	273	11.7	363	210	61	7	11	2	30	65
		401	5	72	79	7.0	299	120	29	7	12	3	41	47
	Pequop Mountains	776	8	103	130	8.9	303	138	36	0	12	3	76	103
	Spruce Mountain	1,366	8	159	197	9.0	450	135	53	1	11	2	90	67
		320	4	53	77	7.2	272	164	25	16	13	4	150	68
Ely	Butte Mountains	336	3	53	76	9.0	169	149	21	3	6	2	116	115
	Egan Range	375	7	76	72	6.2	338	120	30	3	15	4	81	101
		573	13	98	92	6.1	461	80	35	0	15	3	65	87
		1,471	15	142	140	9.7	271	151	38	0	9	3	115	97
		1,383	16	173	141	8.7	340	101	44	4	9	2	110	88
		1,137	10	75	157	10.0	287	145	29	9	7	2	148	145
		803	6	79	112	10.8	175	174	28	1	8	3	95	41
		1,186	11	121	248	8.1	697	141	44	8	13	2	108	77
		668	6	39	122	10.4	205	193	15	10	9	4	122	130
		695	6	81	165	7.8	497	178	37	0	12	2	79	32
	Schell Creek Range	483	5	83	66	10.4	111	117	26	4	6	3	106	117
		304	2	39	75	9.0	168	164	16	15	6	3	78	142
		63	2	21	20	4.8	160	54	12	20	7	4	127	145

After the data were expanded, 16 of the 44 study plots were identified by Meeuwig and Cooper's (1981) criteria as fully stocked. These plots were considered to have maximum volume growth for their respective sites and were used for modeling PLAY.

All modeling analyses were done using regression analysis. Criteria for selecting the best prediction equations were maximum R^2, minimum C.V., and regression residual graphs indicating minimum variance and little prediction bias (see appendix for statistics definitions).

RESULTS

Site Index

Two site index model forms were considered:

$$\ln Y = a + b/X \text{ (Husch and others 1982)} \quad (3)$$

$$\ln Y = a + b \cdot \ln X \text{ (Tausch 1980)} \quad (4)$$

where

Y = height

X = DSH

a = regression coefficient interpreted as site index

b = regression coefficient.

Actual coefficient estimation of the site index equations was done for pinyon and juniper combined, and a separate a_i coefficient (site index) was estimated for each study site using dummy variables:

$$\ln Y = a_1 + a_2 + \ldots + a_i + \ldots + a_{14} + b \cdot Z + c \cdot SP \quad (5)$$

where

a_i = intercept for the ith plot, 0 otherwise

Z = $1/X$ for eq. 3, $\ln X$ for eq. 4

SP = 1 for pinyon, 0 for juniper

b, c = regression coefficients.

The best fitting equation relating height to DSH came from using equation 3 as a model form (eq. 6 in table 2). This equation was converted (for conversion see Husch and others 1982, p. 340) to a site index prediction equation (eq. 7 in table 2). Conversion required a reference (or base) DSH. Following Daniel and others (1966), a 10-inch DSH pinyon was selected as diameter reference.

The site index equation (eq. 6) was graphed (fig. 2) to compare differences between pinyon and juniper site indices. The graph showed that pinyon trees of the same diameter as juniper trees had to be taller to yield comparable site indices. Also apparent from the graph was less height distance (on the y-axis) between site index classes for the juniper curves than for the pinyon curves. This will probably result in less sensitivity of the site index equations for distinguishing between juniper site classes than between pinyon site classes.

The site index equation also was compared (in fig. 3) to a similar site index relationship constructed by Daniel and others (1966, p. 61). There was considerable difference for site indices above 18 feet.

Table 2—Site index and volume growth equations for Nevada[1]

Equation description	Equation formula	Regression statistics[2] R^2	$\sqrt{MSE}$	C.V.	n	Equation number
Height prediction	$HT = 1.0555 \cdot SI \cdot \exp - [3.6778 \cdot D_P + 2.5244 \cdot D_J - 0.3137 \cdot SP]$	0.83	1.99	13%	168	(6)
Site index	$SI = 0.9474 \cdot HT \cdot \exp[3.6778 \cdot D_P + 2.5244 \cdot D_J - 0.3137 \cdot SP]$	—algebraic manipulation of eq. 6—				(7)
Current growth	$PAI = \exp[-1.7821 + 0.7481 \cdot \ln(CRNVOL) + 0.2697 \cdot \ln(BA/D_Q) - 1.4238 \cdot JCOV]$	0.76	2.70	30%	44	(8)
Potential yield	$PLAY = -10.44 + 0.869 \cdot SI$	0.76	2.09	27%	16	(9)
Potential yield, upper bound	$PLAY_{ub} = -8.46 + 0.897 \cdot SI$	—tolerance point regression—				(10)

where

BA = basal area at DSH (ft^2/acre)

CRNVOL = crown volume per acre divided by 1,000 (1,000 ft^3/acre)

Crown area = $0.7854 \cdot CRMX \cdot CRMN$ (ft^2)

Crown volume = $0.5236 \cdot CRMX \cdot CRMN \cdot CRHT$ (ft^3)

CRHT = tree crown height (ft)

CRMN = tree crown diameter perpendicular to CRMX (ft)

CRMX = maximum tree crown diameter (ft)

DSH = tree diameter at 6-inch stump height (inches)

D_J = 1/DSH for juniper, 0 for pinyon

D_P = 1/DSH for pinyon, 0 for juniper

D_Q = quadratic mean DSH (inches)

exp = exponential function

HT = total tree height (ft)

JCOV = proportion of juniper crown area per acre

ln = natural log function

PAI = periodic annual volume growth averaged over 10-year period (ft^3/acre/yr)

PLAY = potential long-term average volume yield for fully stocked stands (ft^3/acre/yr)

$PLAY_{ub}$ = 70th percentile maximum of PLAY (ft^3/acre/yr)

SI = site index (ft) referenced to 10-inch DSH pinyon

SP = 1 for pinyon, 0 for juniper

Volume = gross outside bark volume of all stems and branches larger than 1.5 inches in diameter (ft^3)

[1]These equations and definitions only apply to trees 3 inches DSH and larger.
[2]See appendix.

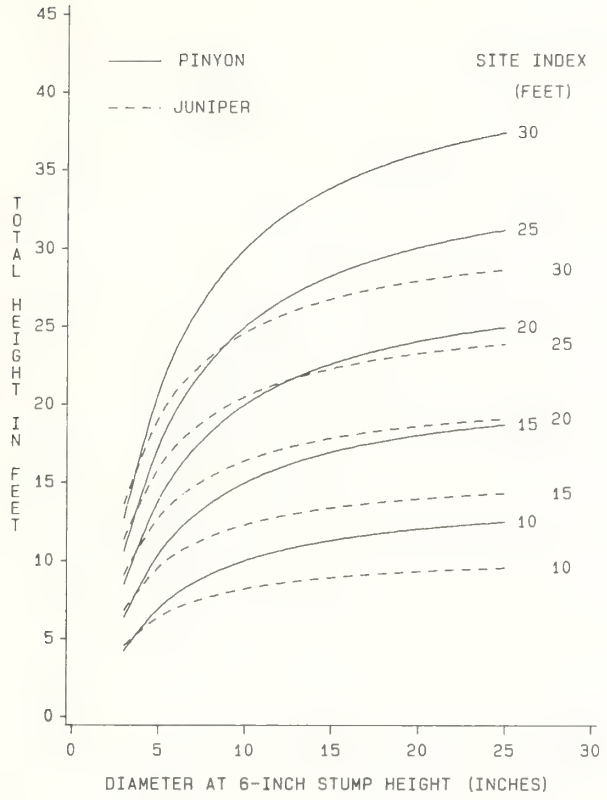


Figure 2—Height-to-diameter site index curves (reference tree is a 10-inch DSH pinyon).

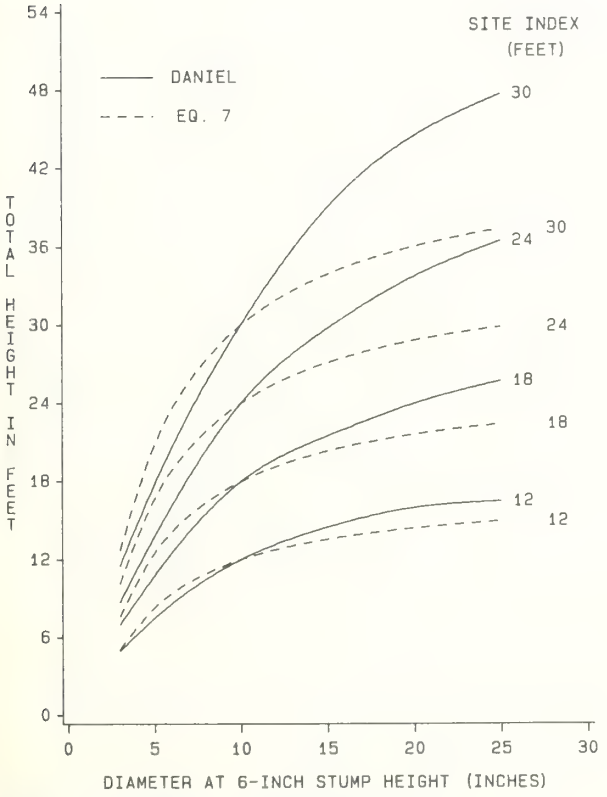


Figure 3—Comparison of Daniel and others' (1966) pinyon site index curves with corresponding pinyon site curves (eq. 7) from this study.

Volume Growth

Site index and other variables collected for this study were examined for PAI growth prediction. The best PAI prediction variable was total crown volume per acre, which explained more than 70 percent of the variation. Next best was a variable for the amount of juniper crown cover for each site. This variable accounted for a decreased growth rate proportional to the amount of juniper cover.

The regression analysis showed some gain from including a third variable in growth prediction models, but the data set was too small to clearly determine the best choice for this variable. Basal area growth had the highest R^2 among choices for a third variable in the PAI model. But because basal area growth is costly and somewhat impractical to obtain, a more practical third variable, basal area divided by quadratic mean DSH, was found. The final PAI equation (eq. 8) is listed in table 2.

PLAY, the measure of potential yield, was predicted from site index (eq. 9 in table 2). This equation gave a least squares average of annual volume yield for fully stocked natural stands.

Another PLAY equation was also developed using the tolerance interval concept from linear model theory (Graybill 1976, p. 270). This concept allows development of an equation that predicts values other than a conventional least squares average (like eq. 9). Statistical tolerance points (somewhat analogous to confidence intervals) enable determination of an upper or lower proportion (called upper or lower tolerance point) for the data distribution under study. In this study, upper 30 percent tolerance points at the 95 percent probability level were computed for each height-to-DSH site index value for fully stocked stands. This means a 30 percent tolerance point for a site index value is its expected maximum PLAY 70 percent of the time. Another regression equation (eq. 10 in table 2) was developed from the 30 percent tolerance points. When compared to the data (in fig. 4) this equation appeared a reasonable upper bound for PLAY prediction. This equation would be appropriate for assessment of the maximum or upper bound PLAY expected for a given site index.

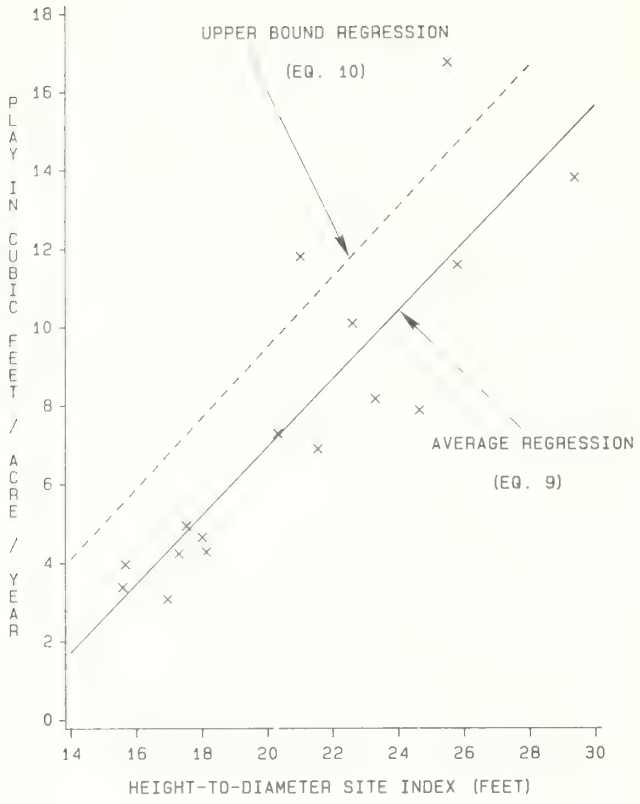


Figure 4—Potential long-term average yield (PLAY) prediction equations overlaid on data from fully stocked stands.

DISCUSSION

The site index and growth equations given in table 2 represent statistical descriptions of data in this study. Users of these results should consider two points not accounted for in the data analysis. First, because the equations in table 2 were mostly developed by empirical regression analysis, they may not apply outside the bounds of the data. Careful study of table 1 and figure 1 should be done before applying the site index and growth equations. A second, more subtle point concerns the line-intersect sampling method used to collect the data. During the analysis, I found suspiciously large blow-up factors from using transects to sample sparse P-J stands comprised of small-crown-diameter trees (see formulas in Meeuwig and Budy 1981). Because few transects per plot were used (see table 1) these problems were compounded. A comparison using thirty-nine 1/10-acre BLM inventory plots from the same sites as the study plots consistently showed larger values computed from the transect data for basal area and for trees per acre. This does not necessarily mean the line-intersect sampling method gives positively biased results for P-J. However, I suspect the relationships described by the equations in table 2 were somewhat affected by the line-intersect method. Had I used fixed-area plots, different model relationships or different equation coefficients may have resulted. Perhaps a more rigorous statistical treatment should be applied to P-J line-intersect sampling than that given by its first proponents, Meeuwig and others (1978).

Aside from sampling considerations, these study results at least meet the need for rough assessment of P-J site index and volume growth. Also the strong relationship found between crown volume and PAI should serve to stimulate future P-J growth research.

REFERENCES

Brickell, J. E. Equations and computer subroutines for estimating site quality of eight Rocky Mountain species. Research Paper INT-75. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1970. 22 p.

Canfield, R. H. Application of the line interception method in sampling range vegetation. Journal of Forestry. 39: 388-394; 1941.

Daniel, T. W.; Rivers, R. J.; Isaacson, H. E.; [and others]. Management alternatives for pinyon-juniper woodlands. Part A: Ecology of the pinyon-juniper type of the Colorado Plateau and the Basin and Range Provinces. Logan, UT: Utah Agricultural Experiment Station; 1966. 242 p.

Graybill, F. A. Theory and application of the linear model. North Scituate, RI: Duxbury Press; 1976. 704 p.

Howell, J. Piñon and juniper: a preliminary study of volume, growth, and yield. Regional Bulletin 71. Albuquerque, NM: U.S. Department of Agriculture, Soil Conservation Service; 1940. 90 p.

Husch, B.; Miller, C. I.; Beers, T. W. Forest mensuration. 3d ed. New York: John Wiley and Sons; 1982. 402 p.

McMahon, T. Size and shape in biology. Science. 179: 1201-1204; 1973.

Meeuwig, R. O.; Budy, J. D. Point and line-intersect sampling in pinyon-juniper woodlands. Research Paper INT-104. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 38 p.

Meeuwig, R. O.; Cooper, S. V. Site quality and growth of pinyon-juniper stands in Nevada. Forest Science. 27(3): 593-601; 1981.

Meeuwig, R. O.; Miller, E. L.; Budy, J. D. Estimating pinyon-juniper cordwood with the line-intersect method. Research Note INT-242. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1978. 8 p.

Tausch, R. Allometric analysis of plant growth in woodland communities. Logan, UT: Utah State University; 1980. 143 p. Ph.D. dissertation.

U.S. Department of Agriculture, Forest Service. Nevada forest survey field procedures, 1980. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Forest Survey; 1980. 125 p.

APPENDIX

This appendix contains equations for goodness-of-fit regression statistics and for site-specific age and volume prediction.

Goodness-of-Fit Statistics

Because many models were developed with transformed data, goodness-of-fit statistics were recomputed after parameter estimation according to the following formulas:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2} \quad (11)$$

$$\text{MSE} = \sum_{i=1}^{n} \frac{(Y_i - \hat{Y}_i)^2}{n-p} \quad (12)$$

$$\text{C.V.} = \sqrt{\text{MSE}}/\bar{Y} \quad (13)$$

where

R^2 = coefficient of determination
MSE = mean square error from regression
C.V. = coefficient of variation
$\hat{Y}_i$ = predicted value of the observation retransformed to original measurement scale
Y_i = ith observation
$\bar{Y}$ = mean of all observations
n = sample size
p = number of model coefficients.

Age and Volume Equations

The following individual tree equations were developed for each plot for age and volume data summary:

$$A_i = \exp[3.6548 + b_i \cdot \ln(\text{DSH}) - 0.1638 \cdot SP] \quad (14)$$

$$V_i = \exp[-6.1090 + b_i \cdot \ln(\text{DSH}) + 0.6750 \cdot SP + 0.1719 \cdot \text{STEM}_\text{P} + 0.4519 \cdot \text{STEM}_\text{J}] \quad (15)$$

where

A_i = age (yrs) for trees in the ith plot
V_i = volume (ft^3) for trees in the ith plot, includes wood and bark for all stems and branches with diameters greater than 1.5 inches
SP = 1 for pinyon, 0 for juniper
DSH = basal diameter (inches) at 6-inch stump height
STEM_P = 1 for single-stem pinyon, 0 for otherwise
STEM_J = 1 for single-stem juniper, 0 for otherwise
b_i = coefficients estimated from data for the ith plot
i = 1 to 44 study plots
ln = natural log function
exp = exponential function

regression statistics

Eq. No.	n	C.V.	R^2
(14)	237	26%	0.75
(15)	247	33%	0.94

Chojnacky, David C. Pinyon-juniper site quality and volume growth equations for Nevada. Research Paper INT-372. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 7 p.

Site quality and volume growth equations were developed for Nevada's pinyon-juniper (P-J) woodlands. Trees at 44 sites were measured for basal stem diameter, crown dimensions, height, age, volume, and stem diameter growth. A site index equation was built from a relationship between tree height and diameter. Two types of stand volume growth equations were constructed. Periodic annual volume growth was predicted from total crown volume, juniper crown cover, basal area, and quadratic mean diameter data. The other type of growth, long-term average annual yield from fully stocked stands, was fit to site index in an equation. Equations are summarized in a table.

KEYWORDS: *Pinus monophylla, Juniperus osteosperma*, site index, periodic annual increment

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-373

December 1986

Adaptive Variation in *Pinus ponderosa* from Intermountain Regions. II. Middle Columbia River System

G. E. Rehfeldt

THE AUTHOR

GERALD E. REHFELDT is a plant geneticist at the Intermountain Research Station's Forestry Sciences Laboratory in Moscow, ID.

RESEARCH SUMMARY

Seedlings representing 138 populations of ponderosa pine from drainages of the middle Columbia River system were grown and compared in common environments. Field studies of 3-year-old trees on mesic and xeric test sites detected population differentiation for traits reflecting growth and development. Populations that expressed the greatest growth potential under mesic culture suffered the greatest reduction in height under xeric culture. Consequently, a different set of populations was performing the best on the two sites when 3-year height was expressed as the growth from a common height at age 2.

Greenhouse studies of the periodicity of shoot elongation revealed that populations of high growth potential achieved a large stature by means of a long duration, late cessation, rapid rate, and large amount of elongation.

Multiple regression models accounted for as much as 60 percent of the variance between populations and described adaptive landscapes in which populations from low elevation have a high growth potential while those from high elevations have a low growth potential. Geographic variation at a common elevation indicated that populations of high growth potential come from areas where the frost-free period is long and precipitation is relatively high. Thus, growth potential is directly related to the length of the growing season, which can be truncated by either frost or moisture stress.

Adaptive landscapes are used to construct guidelines for limiting seed transfer in artificial reforestation. In general, seed from a single source should not be transferred more than $\pm$200 m in elevation.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Adaptive Variation in *Pinus ponderosa* from Intermountain Regions. II. Middle Columbia River System

G. E. Rehfeldt

INTRODUCTION

Populations that occupy contrasting environments tend to differ genetically for numerous traits that convey environmental adaptation. In accordance, adaptive differentiation in the widespread ponderosa pine (*Pinus ponderosa*) is well documented (Wang 1977) and is related to the elevation and geographic origin of the seed. For just the Inland Northwest, populations from mild environments tend to have a high growth potential while populations from areas where growing seasons are short tend to have a low growth potential (Wang 1977; Madsen and Blake 1977; Rehfeldt 1979b, 1980, 1986).

Forest managers rely on geographic patterns of adaptive variation to estimate the distance that seeds can be transferred from their origin before maladaptation begins to limit the productivity of artificial regeneration. However, previous studies were of insufficient power and scope for providing managers with this information. Consequently, a series of studies was begun to determine the appropriate limits to seed transfer for the Intermountain Region. While the first study of this series concerned populations from central Idaho (results published in Forest Science, Rehfeldt 1986), the present involves populations from the middle Columbia River system of northeastern Washington, northern Idaho, and western Montana.

MATERIALS AND METHODS

Population differentiation was studied in seedlings from 138 populations that sampled the ecologic, geographic, and elevational distribution within which the species is of commercial importance in the Inland Northwest (fig. 1). Genetic diversity of each population was sampled in a manner to assure that seedling populations represented a large number of parental trees. Most populations were represented by an equal volume of wind-pollinated cones from 10 trees. Some, however, were represented by samples of cones collected from several squirrel caches. Genetic diversity was assured by selecting cones with a variety of morphologies, sizes, and colors. Seedlings were used in separate studies of (1) growth and development in the field and (2) the periodicity of shoot elongation in a greenhouse. The results from both were used to assess patterns of genetic variation.

Growth and Development

Seedlings were grown for 6 months in plastic containers (65 cm^3) in a shadehouse at Moscow, ID (lat. 48.5° N., long. 116.7° W.). In the fall, seedlings were planted at two sites at about 670 m elevation at the Priest River Experimental Forest, 190 km north of Moscow. Although both sites averaged 90 frost-free days, one was on sandy loam soil and was maintained under a mesic cultural regime. This site was tilled before planting, competing vegetation was controlled, and the planting was irrigated twice each summer during the course of the study. The second site, on glacial till, was maintained under xeric cultural conditions. Irrigation was provided early in the second growing season to ensure seedling establishment, but water supplemental to natural precipitation, which averages 81 cm, was withheld thereafter. This site was also tilled before planting, and competing vegetation, gophers, and white grubs were controlled. Nine seedlings, planted in row plots, represented each population in each of three blocks at each site. At the mesic site, 0.5 m separated rows and 0.3 m separated trees within rows. To allow conversion of the test to a demonstration plot, the corresponding spacings at the xeric site were wider than at the mesic site: 1 m and 0.5 m.

Population performance was described by five variables:

1. Height, the 3-year height (centimeters) of individual trees.
2. Leaf length, the length (centimeters) of a leaf from near the center of the 3-year shoot of an individual tree.
3. Adjusted height, 3-year height (centimeters) of individual trees adjusted by regression on 2-year height, a value that depicts the 3-year height expected if all trees had been the same height at age 2. Consequently, the value is relatively independent of early environmental effects (such as seed weight or transplanting shock) and genetic effects and is capable of reflecting the adaptive response of populations to a particular environment in a relatively short time.
4. Xeric height reduction, the amount (centimeters) by which the height of trees cultured under xeric conditions failed to reach the potential expressed under mesic conditions. The value was calculated as the difference between the xeric height of an individual tree and the mean mesic height of the population from which the individual originated.

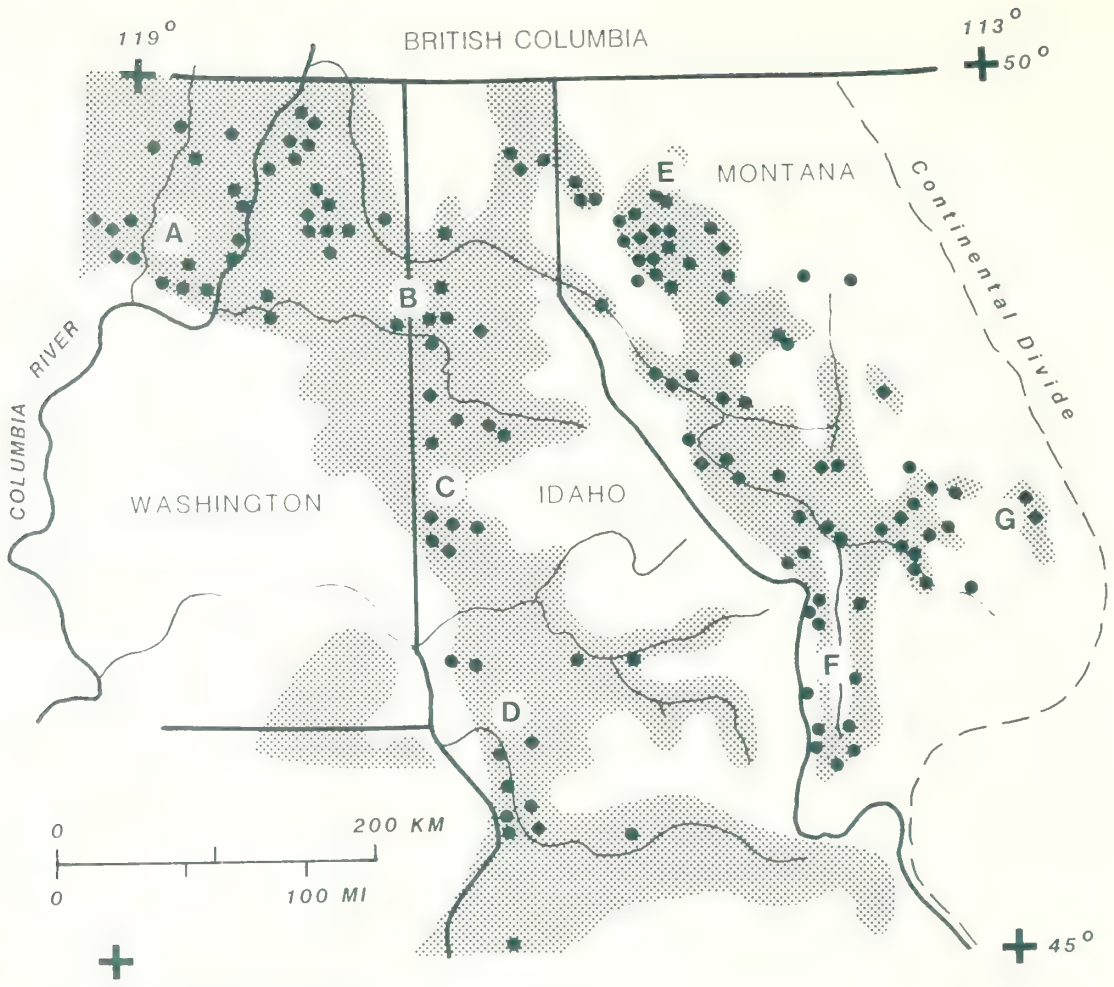


Figure 1—Geographic distribution of ponderosa pine (shading) within the major drainages of the middle Columbia River system and location of sampled populations. Letters A to G locate the elevational clines presented in figure 2.

5. Drought mortality, the proportion of trees within each plot that died from drought under xeric conditions.

Analyses of variance were performed on each variable according to a model in which the effects of populations, planting sites, and blocks within sites were considered as random variates. A harmonic mean of 7.31 reflected the number of seedlings in each block.

Periodicity of Shoot Elongation

Seedlings from 98 of the populations were grown for 2 years in plastic containers (740 cm^3) in a shadehouse at Moscow. Each population was represented by nine seedlings in each of three blocks. In mid-March of the second growing season, seedlings were moved into a greenhouse before shoot elongation had begun. Greenhouses were maintained under natural photoperiods and light intensities. Temperatures were held at about 24±3 °C during the day and were allowed to cool to a minimum 13 °C at night. All seedlings were measured three times each week until elongation was well under way. Thereafter, measurements were made twice each week until elongation of the preformed shoot had ceased.

As described by Rehfeldt and Wykoff (1981), shoot elongation of individual trees was expressed by a modified logistic function with a hyperbolic time term:

$$Y = [1 + be^{r(X - X_0)}]^{-1}$$

where Y is the proportion of total increment attained by day X; b, r, and c are regression coefficients; and e is the base for natural logarithms.

Regression statistics allowed calculation of the following variables for describing the periodicity of shoot elongation of individual seedlings: (1) initiation of elongation: the day on which 2 mm of growth had occurred; (2) cessation of elongation: the day on which all but 2 mm of growth had occurred; (3) duration of elongation: the number of days between initiation and cessation; (4) rate of elongation: elongation (millimeters) per day during the period of maximum elongation; and (5) total elongation (millimeters).

Population differentiation was assessed according to an analysis of variance in which the effects of populations and blocks were considered to be random. A harmonic mean of 8.83 reflected the number of seedlings from each population in each block.

Patterns of Genetic Variation

Multiple regression models were used to relate genetic variation between populations to the elevation and geographic location of the seed source. Independent variables included elevation, latitude, longitude, northwest departure, southwest departure, and their squares. Squared values were used to accommodate the possibility of nonlinear patterns of variation. Northwest and southwest departures were derived by rotating the grid of latitude and longitude by 45°. Elevation was considered without geographic interaction because preliminary analyses suggested that the relationship between performance and elevation was similar throughout the region of study. Thus, 10 independent variables were included in a stepwise regression for maximizing R^2 (SAS 1982) according to the general model:

$$Y_i = \beta_0 + \sum_j \beta_1 X_{ij} + \sum_j \beta_2 X_{ij}^2$$

where Y_i is the performance of population i; X_{ij} is independent variable j for population i; and β_0, β_1, and β_2 are regression coefficients, $j = 1 \ldots 5$.

Adequacy of a model was judged according to the goodness of fit (R^2), residual variance ($s_{y \cdot x}$), patterns displayed by residuals (Draper and Smith 1981), and the degree by which results were biologically plausible.

RESULTS

The analyses detected differences between populations for numerous traits involving (1) growth and development and (2) the periodicity of shoot elongation. Genetic variation in these traits was related to the elevation and geographic origin of the seed.

Growth and Development

Planting sites had a tremendous effect on the growth and development of seedlings. Under mesic cultural conditions, the average 3-year-old tree was 46 cm tall with leaves 14 cm long, but under xeric conditions, the average tree was only 23 cm tall with leaves 7 cm long. Thus, xeric culture reduced the growth potential expressed under optimal growing conditions by an average of 23 cm. Values of adjusted height show that if trees on both sites had been the same height at age 2, those growing under the mesic regime would still have been 11 cm taller at age 3 than trees on the dry site even though 3-year height accounted for 69 percent of the variance in 2-year height.

Because of these differences associated with cultural conditions, main effects of test sites accounted for most (68 to 85 percent) of the variance for those variables measured on both sites and, therefore, dominate analyses of variance (table 1). Nevertheless, differences between populations were detected for all variables measured on both sites even though the main effects of populations accounted for less than 5 percent of the total variance (table 1).

The significant interactions (table 1) for height and adjusted height indicate that the differences between populations on one site were not the same as the differences between the same populations on the other site. Because these interactions accounted for nearly a third as much variance as the main effects of populations, subsequent analyses involving population means will consider height and adjusted height from each site as separate variables. By contrast, the lack of a significant interaction for leaf length shows that the relative performance of populations was similar at each site even though leaves were much shorter under xeric conditions.

Populations also differed significantly in the reduction in height attributable to xeric culture. The absolute amount of reduction ranged from 28 cm (56 percent) for one population to 14 cm (43 percent) for another. But populations did not differ in mortality under xeric conditions because drought mortality reached only 16 percent and was confined to essentially one block.

Periodicity of Shoot Elongation

Shoot elongation of individual seedlings was completed between 31 and 53 days after being placed in the greenhouse. This means that 11 to 17 observations were

Table 1—Results of analyses of variance of growth and development in field environments presented as intraclass correlations, the ratio of a variance component to the sum of all components

Source of variance	Variable				
	3-year height	Adjusted height[1]	Leaf length	Xeric height reduction[2]	Drought mortality
Sites	0.850**	0.689**	0.850**	—	—
Blocks in site	.000	.002**	.008**	0.006**	0.977**
Populations	.028**	.021**	.004**	.317**	.012
Sites × populations	.010**	.009**	.002	—	—
Experimental error	.007**	.047**	.020**	.103**	.010
Within plots	.106	.232	.116	.574	—
Error mean square[3]	107.433	72.969	5.824	3.119	.027

**Statistical significance of the F-value at the 1 percent level of probability.
[1]3-year height adjusted by regression on 2-year height.
[2]Difference between xeric height and the growth potential expressed by mesic height.
[3]Absolute value of the interaction mean square that was used to test for differences between populations.

Table 2—Results of analyses of variance for the periodicity of shoot elongation presented as intraclass correlations, the ratio of a variance component to the sum of all components

Source of variance	Variable				
	Elongation	Initiation	Cessation	Duration	Rate
Replications	0.04**	0.03**	0.01**	0.01**	0.07**
Populations	.20**	.02**	.34**	.17**	.15**
Interaction	.05**	.09**	.16**	.03**	.06**
Within plots	.71	.86	.49	.79	.71
Error mean square[1]	766.931	4.811	18.109	22.553	1.428

**Significance of the F-value at the 1 percent level of probability.
[1]Absolute value of the interaction mean square that was used to test for differences between populations.

Table 3—Results of stepwise regressions for relating genetic variation to the elevation and geographic origin of the seed

Variable	Number of independent variables	R^2	Residual mean square
Growth and development			
3-year mesic height	5	0.52**	10.09
3-year xeric height	6	.31**	4.55
Adjusted mesic height	6	.17**	2.14
Adjusted xeric height	6	.13**	1.91
Leaf length	5	.10**	.20
Xeric height reduction	8	.40**	6.20
Periodicity of shoot elongation			
Elongation	5	.49**	86.98
Initiation	5	.09	.24
Cessation	6	.59**	1.74
Duration	5	.58**	1.89
Rate	6	.43**	.14

**Statistically significant at the 1 percent level.

available for the logistic regression that described shoot elongation of individual trees nearly perfectly. Values of R^2 ranged from 0.90 to essentially 1.0, averaging 0.99.

Analyses of variance not only detected significant differences between populations for all variables (table 2) but also attributed substantial variance to the effects of populations for all variables except the initiation of shoot elongation. These effects were reflected in mean differences between populations as large as 9 days in cessation, 10 days in duration, 2.8 mm per day in rate, 73 mm total elongation, but only 2.3 days in initiation. Although these differences seem small, culturing plants under optimal conditions allows shoot development to proceed rapidly, and developmental events are condensed into a short time interval. Under natural conditions development occurs over a long period and differences in the periodicity of shoot elongation become relatively large.

Patterns of Genetic Variation

By accounting for as much as 60 percent of the variance between populations, regression models were statistically significant for all variables except the initiation of shoot elongation (table 3) and drought mortality, two variables for which population differentiation was not pronounced (tables 1 and 2). Thus, genetic differences between populations follow systematic patterns that can be related to the elevation and geographic origin of the seed. These patterns can be presented as (1) elevational clines for several geographic localities (fig. 2), (2) geographic clines at a constant elevation (fig. 3), or (3) geographic clines at the base elevation, the lowest elevation at which the species occurs in a given locality (fig. 4).

These results, however, were based on five to eight independent variables and, therefore, are susceptible to overfitting, a condition that occurs when models are fit to single samples rather than to general trends described by all samples (Draper and Smith 1981). Consequently, in this paper, population differentiation is interpreted according to the least significant difference (Steel and Torrie 1960) at the 80 percent level of probability—$lsd(0.2)$. A relatively low level of probability is used to guard against accepting no differences between populations when differences actually exist. Thus, in figure 2, populations separated by an elevational interval sufficient to subtend a mean difference equal to $lsd(0.2)$ are judged to be statistically different at

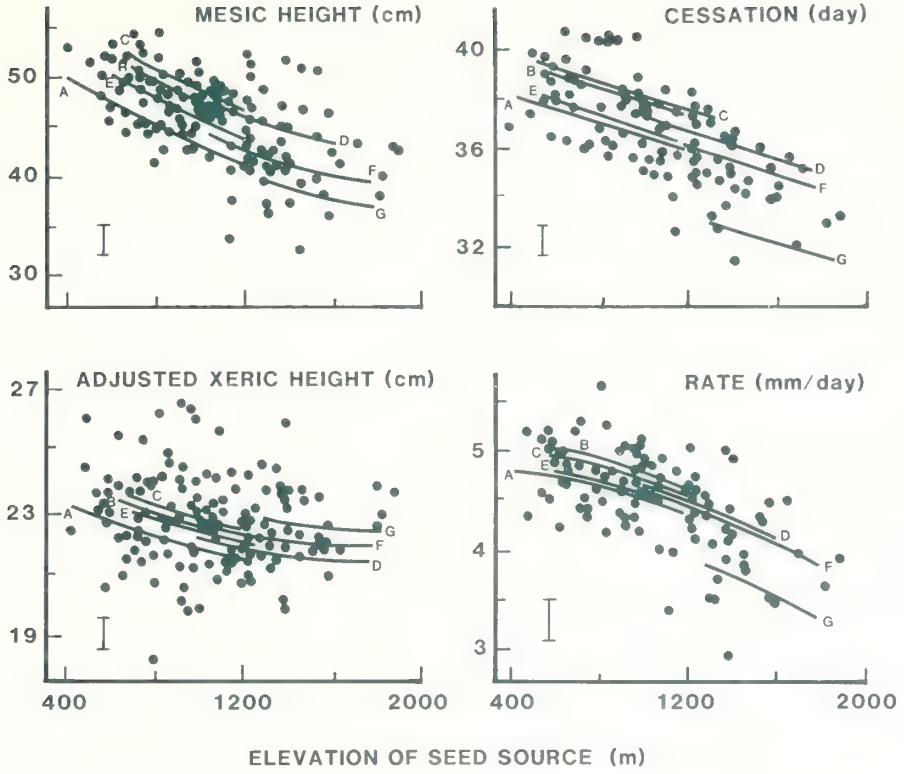


Figure 2—Elevational clines for four variables at seven geographic locations keyed to figure 1. Brackets quantify lsd (0.2)

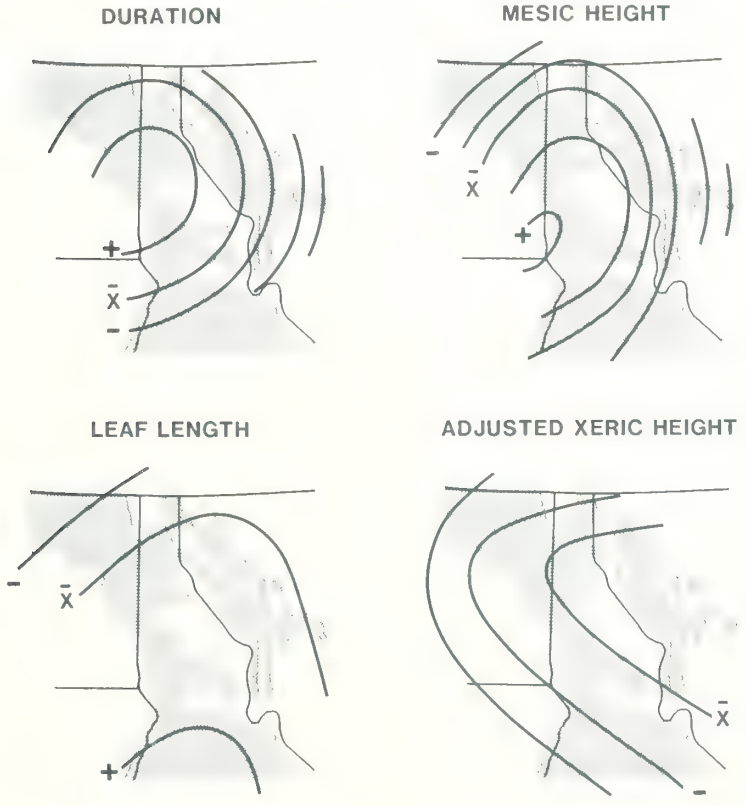


Figure 3—Geographic patterns of variation for four variables described by isopleths (contour lines) of equal performance at the mean elevation (1,075 m). The interval between isopleths equals ½[lsd (0.2)]. Isopleths represent positive or negative deviations from the mean value ($\bar{x}$) of all populations.

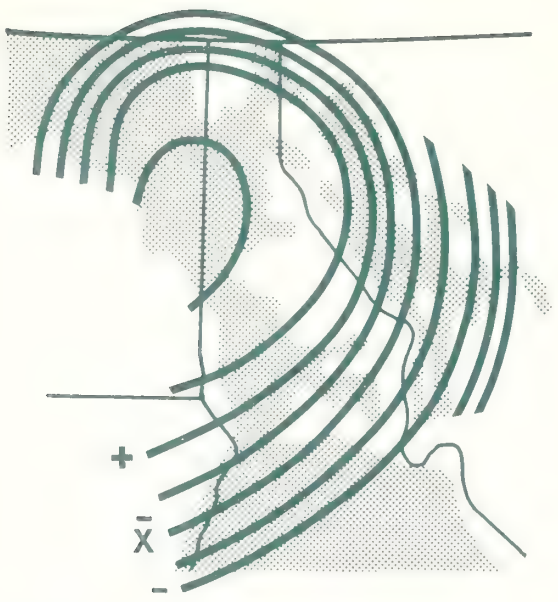


Figure 4—Geographic patterns of variation for mesic height presented as isopleths of equal performance for base elevations, the lowest elevation at which ponderosa pine occurs in a given area. The interval between isopleths equals ½[lsd(0.2)]. Isopleths represent positive or negative deviations from the mean ($\bar{x}$) of all base populations.

about the 80 percent level of probability. In figures 3 and 4, the distance between isopleths (contour lines) is scaled to ½[*lsd*(0.2)]. This means that populations separated by a distance equivalent to two isopleths are assumed to differ with a probability of about 0.2.

The relationship between the elevation of the seed source and population performance is presented in figure 2 for four variables that span the range of responses for all variables. Not shown are the elevational clines for adjusted mesic height and xeric height reduction, which nearly duplicated that for mesic height. Clines for the cessation and amount of shoot elongation were similar to that of the duration of elongation, and clines for adjusted xeric height, leaf length, and the initiation of shoot elongation failed to depict differentiation in excess of *lsd*(0.2).

These elevational clines indicate that growth potential decreases as elevation of the seed source increases. In contrast to populations from high elevations, those from low elevations tend to be tall, they exhibit a late cessation, long duration, and rapid rate of elongation, and under xeric culture, their growth is reduced the most.

The elevational interval associated with a mean difference between populations that equals *lsd*(0.2) is approximately 440 m for the linear cline involving cessation of shoot elongation (fig. 2). Although the interval for the nonlinear clines would change as elevation changes (fig. 2), population differentiation at the mean elevation (1,075 m) can be detected across about 400 m for both mesic height and adjusted xeric height, but about 450 m for rate of elongation.

Geographic patterns of variation at the mean elevation are illustrated in figure 3 for the four variables that represent the range of patterns. Patterns for all variables not presented follow those for the duration of shoot elongation and mesic height. Thus, when comparing populations from the same elevation, populations from west central areas display the largest values of traits reflecting growth potential. From this area, growth potential declines in all directions.

Patterns for adjusted xeric height and leaf length deviate from the general. Figure 3 shows that if all populations had been the same height at age 2, those from the dry lands to the east would have been tallest (largest adjusted xeric height) at age 3 on the xeric site. Geographic clines for leaf length indicate that southern populations have the longest leaves while those from the northwest have the shortest.

Because geography and elevation are not independent of each other, genetic variation between populations at the base elevation (fig. 4), the lowest elevation at which ponderosa pine occurs in a given locality, is arranged along much steeper clines than variation at a constant elevation (fig. 3). As judged by the number of and distance between isopleths, geographic clines at the base elevation are nearly twice as steep as those for a constant elevation. Figure 4 shows that populations of the highest growth potential should come from among base populations from the west central region. From this area, growth potential of base populations decreases regardless of whether elevation is decreasing toward the northwest or increasing toward the south or east. The average distance between differentiated populations occurs on a relatively small scale (54 km) across the landscape.

Similarities in patterns of variation between the variables (figs. 2 and 3) result from intercorrelations, some of which are extremely strong (table 4). Populations that were tall under mesic conditions exhibited other characters associated with a high growth potential: a late cessation, long duration, fast rate, and large amount of shoot elongation. Although these same populations tended to be the tallest under xeric culture (table 4), they suffered the greatest xeric height reduction in that the growth potential expressed under mesic culture was reduced the most by xeric culture.

DISCUSSION

Results have demonstrated genetic differentiation between populations for a variety of loosely intercorrelated traits. These intercorrelations, such as those in *Pseudotsuga menziesii* (Rehfeldt 1983b), *Pinus contorta* (Rehfeldt 1983a), and *P. ponderosa* from central Idaho (Rehfeldt 1986), involve traits that are part of an annual sequence of developmental events. This sequence begins with dehardening in the spring, includes shoot elongation, leaf expansion, bud development, and lignification, and concludes with cold acclimation. The components are intercorrelated because the entire sequence must fit into a growing season of finite length. Thus, populations that inhabit environments where growing seasons are short cease developmental events early and are, therefore, short, even when grown under optimal conditions.

For ponderosa pine, a species that commonly occurs in habitats that border the prairie, the growing season may

Table 4—Simple correlations among population means. Underlined coefficients failed to reach statistical significance at the 5 percent level.

Variable	Code	H3-X	AH-M	AH-X	LL	RED	DD	EL	IN	CES	DUR	RATE
Growth and development												
3-year mesic height	H3-M	0.74	0.56	0.31	0.30	0.84	0.02	0.76	−0.14	0.68	0.68	0.74
3-year xeric height	H3-X		.28	.69	.35	.25	−.18	.64	−.14	.48	.50	.64
Adjusted mesic height	AH-M			.19	−.02	.57	.04	.31	−.02	.30	.29	.29
Adjusted xeric height	AH-X				.22	−.11	−.29	.24	−.01	.17	.16	.24
Leaf length	LL					.15	−.18	.21	−.18	.08	.12	.23
Xeric height reduction	RED						.18	.55	−.08	.56	.56	.53
Drought mortality	DD							−.07	.07	.03	.01	−.06
Periodicity of shoot elongation												
Elongation	EL								−.37	.82	.87	.98
Initiation	IN									−.06	−.29	−.37
Cessation	CES										.97	.72
Duration	DUR											.78
Rate	RATE											

be limited by drought or frost or both. The species inhabits environments that differ by over 60 days in frost-free period and by 60 cm in precipitation (fig. 5). That populations have become differentially adapted to environmental differences of this magnitude is an expected result of natural selection.

Adaptive differentiation can be expressed by significant interactions involving populations and environments. However, the interactions that were evident for 3-year height and adjusted height arose for different reasons. On the one hand, the interaction for 3-year height represents a scale effect rather than an adaptive response. As evidenced by strong simple correlations (table 4), populations retained similar rankings in each environment, but the absolute difference in height of any two populations was greater under mesic than under xeric conditions.

On the other hand, the interaction for adjusted height reflects differential adaptation. Under mesic culture, populations of greatest growth potential would still have been tallest at age 3 even if all trees had been the same height at age 2. Thus, the superiority of these populations has increased between ages 2 and 3. But under xeric conditions, populations from dry eastern areas grew the most from a common height at age 2. This suggests that if xeric culture were to be maintained, these eastern populations would eventually become tallest on this particular site.

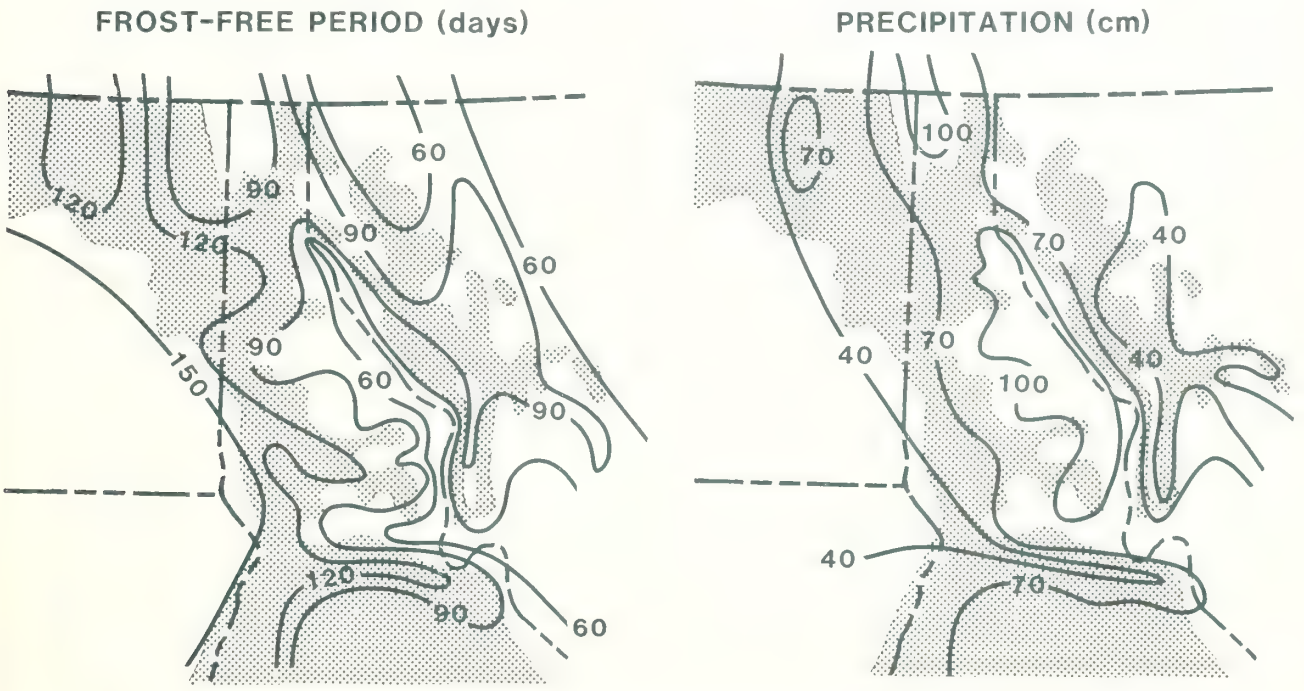


Figure 5—Regional environmental patterns of variation (enlarged from U.S. Department of Commerce 1968).

Regression models described population differentiation according to the elevation and geographic location of the seed source. As elevation increases, the length of the frost-free period rapidly decreases. Baker (1944) has shown that the frost-free period in the Inland Northwest varies by about 80 days across an elevational interval of 1,000 m. Consequently, populations from low elevation generally exhibit a high growth potential associated with a long duration and late cessation of elongation. Populations from high elevation express a low growth potential largely because developmental events must be completed within a short frost-free period. These general trends are remarkably similar to those described by the height of 2-year-old trees growing in nursery beds (Madsen and Blake 1977) and also are similar to the patterns exhibited by populations from central Idaho (Rehfeldt 1986). For both central Idaho and the Inland Northwest, an elevational interval of about 400 m is sufficient for detecting (80 percent level of probability) population differentiation.

Geographic patterns of genetic variation at either a constant or the base of elevation (figs. 3 and 4) were pronounced, consistent, and uniform. Moreover, these patterns roughly correspond to geographic patterns in precipitation and in the frost-free period (fig. 5). Populations of highest growth potential tend to occur in the west-central region where frost-free periods are long and precipitation is relatively high. From this area, growth potential of populations decreases in all directions in a pattern that is similar to that of the frost-free period. Toward the northwest, however, the rapid decline in growth potential is associated with only a small decline in the frost-free period but with a huge reduction in precipitation. Thus, the northwestern populations, which may originate from the lowest elevations (400 m), display a low growth potential. In addition, the eastern populations that exhibited the lowest growth potentials come from areas characterized by both low precipitation and a short frost-free period.

The elevational cline is much steeper than the geographic. In figure 3, the distance between any two isopleths represents half the distance required to detect (80 percent level of probability) genetic differentiation at a constant elevation. Because differentiation can be detected between populations separated by about 400 m in elevation, the distance between geographic isopleths represents the amount of genetic variation that occurs across 200 m of elevation at a single locality. Thus, the total amount of geographic variation that occurs within the region at a constant elevation can also occur across 1,000 m at a single locality.

Regardless, adaptive differentiation occurs along two interdependent clines. This means that populations of similar adaptive norms recur at different elevations across the landscape. As shown in figure 2, populations with a relatively long duration of shoot elongation, 38 days, occur at about 700 m at locality A (fig. 1), 750 m at E, 1,000 m at D, and 1,300 m at both A and B. Thus, similar genotypes are distributed across the landscape in a pattern that is oblique to elevation.

Because patterns of genetic variation are systematically related to environmental variation, one logically accepts the patterns as reflecting adaptive differentiation. As such, the patterns have direct application to artificial reforestation. To maximize productivity, planted trees must be adapted to the planting site. Adaptation is secured by limiting the distance that seeds are transferred from their origin. Consequently, limits to seed transfer must reflect geographic and elevational patterns of variation.

One estimate of an appropriate limit to seed transfer is the smallest geographic or elevational interval across which differentiation is detected (Rehfeldt 1979a). Differentiation along the steepest elevational clines (fig. 2) suggests that a seed zone for ponderosa pine should encompass not more than 400 m of elevation. This means that seed from a single source should not be transferred more than ± 200 m. In addition, the geographic clines of figure 3 describe seed zones that should not encompass more than two geographic bands between isopleths. Approximately three geographic zones would be suitable for the region, and seeds from a single source should not be transferred a distance equivalent to more than ± 1 band.

Although seed zoning is an administratively simple procedure for limiting seed transfer, the procedure tends to be inflexible, inefficient, and uneconomical. This is because seed zones compartmentalize continuous genetic variation and fail to take advantage of the recurrence of similar genotypes at different elevations in geographically separated localities.

By contrast, floating transfer guidelines are based on the recurrence of similar environments in a pattern that is oblique to elevation. According to floating guidelines, seed can be transferred across isopleths (fig. 3), but each time seed is transferred across a geographic interval equaling the interval between isopleths, the elevations at which the seed is to be used should be adjusted. When transferring across isopleths of high to low value, the interval should be adjusted downward by 200 m. When transferring from lower to higher value, the interval should be adjusted upward by 200 m.

For example, assume that seed originates from 1,000 m on the isopleth representing the mean of all populations (fig. 3). This seed should be used between 800 and 1,200 m in lands adjacent to the isopleth. In transferring the seed across one isopleth of larger value, the seed should be used between 1,000 and 1,400 m. Transfers of two contours should be used between 1,200 and 1,600 m. And in transferring the seed across an isopleth of lesser value, the seed should be used between 600 and 1,000 m. In this way, seed from a single source or seed orchard can serve a much broader geographic area than under the concept of discrete seed zones.

These recommendations for limiting seed transfer evolved from statistical models based on the performance of young trees under controlled conditions. The models need practical verification. On the one hand, the environmental events responsible for the systematic patterns may

occur so infrequently that managers might risk transferring fast-growing populations into severe environments in an attempt to increase productivity. Indeed, genetic differentiation may have been detected at levels associated with productive differences so small as to be immaterial. On the other hand, small adaptive differences observed at young ages may portend large differences in the future. Regardless, verification can come only from planting programs that not only incorporate these guidelines but also maintain precise records on the exact location from which planted trees originated. Productivity of such plantings will test the applicability of these guidelines.

REFERENCES

Baker, F. S. Mountain climates of the western United States. Ecological Monographs. 14: 223-254; 1944.

Draper, N. R.; Smith, H. Applied regression analyses. New York: Wiley and Sons; 1981. 407 p.

Madsen, J. L.; Blake, G. M. Ecological genetics of ponderosa pine in the northern Rocky Mountains. Silvae Genetica. 26: 1-8; 1977.

Rehfeldt, G. E. Ecological adaptations in Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) populations. I. North Idaho and northeast Washington. Heredity. 43: 383-397; 1979a.

Rehfeldt, G. E. Genetic variation in southern Idaho progeny tests after 11 years. General Technical Report INT-75. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1979b. 12 p.

Rehfeldt, G. E. Genetic gains from tree improvement of ponderosa pine in southern Idaho. Research Paper INT-236. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980. 9 p.

Rehfeldt, G. E. Adaptation of *Pinus contorta* populations to heterogeneous environments in north Idaho. Canadian Journal of Forest Research. 13: 405-411; 1983a.

Rehfeldt, G. E. Ecological adaptations in Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) populations. III. Central Idaho. Canadian Journal of Forest Research. 13: 626-632; 1983b.

Rehfeldt, G. E. Adaptive variation in *Pinus ponderosa* from Intermountain regions. I. Snake and Salmon River basins. Forest Science. 32: 79-92; 1986.

Rehfeldt, G. E.; Wykoff, W. R. Periodicity of shoot elongation among populations of *Pinus contorta* from the northern Rocky Mountains. Annals of Botany. 48: 371-377; 1981.

SAS Institute. SAS user's guide: statistics. Cary, NC: SAS Institute, Inc.; 1982. 584 p.

Steel, R. G. D.; Torrie, J. H. Principles and procedures of statistics. New York: McGraw-Hill; 1960. 481 p.

Wang, C. Genetics of ponderosa pine. Research Paper WO-34. Washington, DC: U.S. Department of Agriculture, Forest Service; 1977. 24 p.

U.S. Department of Commerce. Climatic atlas of the United States. Washington, DC: U.S. Department of Commerce, Environmental Data Service; 1968. 80 p.

☆U.S. GOVERNMENT PRINTING OFFICE:1986—773-039/41030

Rehfeldt, G. E. Adaptive variation in *Pinus ponderosa* from Intermountain regions. II. Middle Columbia River system. Research Paper INT-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 9 p.

Seedling populations were grown and compared in common environments. Statistical analyses detected genetic differences between populations for numerous traits reflecting growth potential and periodicity of shoot elongation. Multiple regression models described an adaptive landscape in which populations from low elevations have a high growth potential while those from high elevations have a low growth potential. Patterns of genetic variation reflect adaptation to a growing season of variable length. Adaptive landscapes are used to construct guidelines for limiting seed transfer in artificial reforestation. In general, seed from a single source should not be transferred more than ±200 m in elevation.

KEYWORDS: microevolution, genetic differentiation, seed zones, seed transfer

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors

Several Station units conduct research in additional western States, or have missions that are national or international in scope

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-374

December 1986

Distribution of Active Ectomycorrhizal Short Roots in Forest Soils of the Inland Northwest: Effects of Site and Disturbance

Alan E. Harvey
Martin F. Jurgensen
Michael J. Larsen
Joyce A. Schlieter

THE AUTHORS

ALAN E. HARVEY is a supervisory plant pathologist, Intermountain Research Station, Forest Service, U.S. Department of Agriculture, Ogden, UT, located in Moscow, ID.

JOYCE A. SCHLIETER is a statistician for the Intermountain Research Station, located in Missoula, MT.

MARTIN F. JURGENSEN is a professor of forest soils, School of Forestry and Wood Products, Michigan Technological University, Houghton.

MICHAEL J. LARSEN is a principal mycologist, Center for Forest Mycology Research, Forest Products Laboratory, Forest Service, U.S. Department of Agriculture, Madison, WI.

RESEARCH SUMMARY

An examination of the distribution of active ectomycorrhizal short roots among soil components of eight old-growth stands representative of the important timber growing lands of the Inland Northwest revealed a disproportionate concentration in surface organic materials. A similar concentration in the forest floor was present in six second-growth stands of various ages from the subalpine fir and Douglas-fir habitat series of western Montana. Exceptions to this trend were noted only in an extremely dry, old-growth, ponderosa pine stand and a highly disturbed site regenerating to a pure stand of young western larch. Even in these exceptional cases, ectomycorrhizal activities were concentrated in shallow mineral horizons relatively rich in organic materials. There was considerable variation in the quantity of soil organic materials on the 14 sites. In general, harsh and disturbed sites tended to have the least. The relative proportions of soil organic components (litter, humus, decayed wood) changed significantly both within and between sites. Distribution of active ectomycorrhizal short roots among those components during the early summer months was also significantly different, both within and between sites. Approximately 75 percent of active ectomycorrhizal short roots occurred in organic materials that represented only the first 4 cm of the soil depth. This disproportionate role of surface organic materials in supporting critical symbiotic processes emphasizes the need to carefully manage this important soil resource in forested ecosystems throughout the Inland West.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Distribution of Active Ectomycorrhizal Short Roots in Forest Soils of the Inland Northwest: Effects of Site and Disturbance

Alan E. Harvey
Martin F. Jurgensen
Michael J. Larsen
Joyce A. Schlieter

INTRODUCTION

Recognition of the importance of symbiotic, ectomycorrhizal associations to survival and growth of forest trees (Vozzo and Hacskaylo 1971) has provided impetus for extensive research on conditions required to maintain this critical activity in forest soils. Soil conditions are of particular importance in altering the ability of ectomycorrhizal fungi and their hosts to start the association (Bjorkman 1970). Any forestry operation likely to alter soil conditions in a substantial way may change, perhaps reduce, the ability of soil to support ectomycorrhizal associations and attendant host growth. Because the fungi involved in ectomycorrhizal associations are obligatorily dependent on their host trees (Hacskaylo 1973), populations are reduced after harvest. Researchers have studied disturbance-caused changes of mycorrhizal populations (Danielson 1984) and reductions of mycorrhizal inoculum potential (Pilz and Perry 1984). Even in the relatively good soils of the Pacific Northwest, failure to initiate an adequate level of ectomycorrhizal activity can limit survival and performance of young conifers (Christy and others 1982; Trappe and Strand 1969).

Extensive examination of the distribution of forest tree feeder roots (Herman 1977) and ectomycorrhizal short roots (Fogel and Hunt 1979; Harvey and others in press; Meyer 1973; Mikola and others 1966; Vogt and others 1981) have shown that (1) they tend to occur at a shallow depth in the soil, and (2) they are usually associated with organic soil horizons, particularly in older stands (Fogel and Hunt 1979; Harvey and others 1976; Harvey and others in press; Vogt and others 1981).

Frequently the association of ectomycorrhizal activities with soil organic matter has specifically been with decayed wood (Harvey and others 1976, in press; McFee and Stone 1966; McMinn 1963; Trappe 1965). Decaying logs and soil wood are recognized as a unique ecosystem in Northwestern forests (Harvey and others in press; Maser and Trappe 1984) that represent an important source of nutrients and moisture (Barr 1930; Harvey and others 1978; Larsen and others 1980; Place 1950). Harvey and coworkers (1978, 1979) have shown that the distribution of ectomycorrhizal activities in decayed soil wood, as compared to the forest floor and mineral soil, changed with both season and site. Decayed wood supported relatively high mycorrhizal activity during dry seasons and on dry sites. The levels of decayed wood in the Inland Northwest may be affected by the trend toward greater use of harvesting residue, and this could have an impact on future site productivity (Jurgensen and others 1977).

The strong participation of the forest floor and shallow mineral horizons in nutrient cycling of many Inland Northwest forest ecosystems has led to concern regarding management (disturbance) of these important resources throughout the Inland West (Harvey and others in press). The purpose of this study was to investigate the involvement of surface soil components in ectomycorrhizal processes over (1) a wide range of mature ecosystems (habitat types) distributed throughout the Inland Northwest and (2) a range of site disturbance types within a local geographical area on similar habitat types.

STUDY SITES

A summary of site characteristics is provided in table 1.

Sample Sites, Old-Growth

Eight old-growth sites were chosen to be representative of a wide range of climatic and geographic conditions of the Inland Northwest, with emphasis on habitat series (Pfister and others 1977) most commonly associated with commercial forests. These sites had no history of human disturbance.

Site 1 (WH-M) is a western hemlock climax (habitat series) in northwestern Montana on the Coram Experimental Forest. It has a northwest aspect, a slope averaging 15 percent, and an elevation of approximately 1,000 m above mean sea level. The primary ectomycorrhizal host on this site is 250-year-old western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). Western larch (*Larix occidentalis* Nutt.) and western redcedar (*Thuja plicata* Donn.), the latter essentially a nonhost, also occur occasionally.

Table 1—A summary of site characteristics

Site number and acronym	Location	Aspect	Slope percent	Habitat series[1]	Dominant tree	Age	Treatment[2]
						Years	
1(WH-M)[3]	Western Montana	NW	15	Western hemlock	Western hemlock	250	Undisturbed
2(SAF-M)	Western Montana	E	55	Subalpine fir	Subalpine fir	250	Undisturbed
3(DF-M)	Western Montana	S	27	Douglas-fir	Douglas-fir	250	Undisturbed
4(WH-I)	Northern Idaho	E	5-15	Western hemlock	Western hemlock	250	Undisturbed
5(WWP-I)	Northern Idaho	NW	0-10	Western hemlock	Western white pine	250	Undisturbed
6(GF-I)	Northern Idaho	W	30-40	Grand fir	Western hemlock	250	Undisturbed
7(SAF-WY)	Northwestern Wyoming	N	15-25	Subalpine fir	Lodgepole pine	165	Undisturbed
8(PP-W)	Eastern Washington	W	15-35	Ponderosa pine	Ponderosa pine	200	Undisturbed
9(MIX-i)	Western Montana	E	40	Subalpine fir	Douglas-fir	80	WF
10(LPP-i)	Western Montana	W	5	Douglas-fir	Lodgepole pine	50	WF
11(WL-y)	Western Montana	N	10-20	Subalpine fir	Western larch	15-25	CC-BB
12(DF-i)	Western Montana	W	5-15	Douglas-fir	Douglas-fir	60-120	I-SC
13(PP-i)	Western Montana	SW	50-55	Douglas-fir	Ponderosa pine	80-100	PC-UB
14(LPP-y)	Western Montana	W	5	Subalpine fir	Lodgepole pine	15	WF

[1]Habitat series (Pfister and others 1977).
[2]Undisturbed = no history of human disturbance, WF = wildfire, CC-BB = clearcut-broadcast burn, I-SC = intermittent selective cut, PC-UB = partial cut with underburn.
[3]Beginning letters denote primary ectomycorrhizal host, last letters indicate State (caps) and age (lower case); i = intermediate age, y = young age.

Site 2 (SAF-WY) is a subalpine fir climax in northwestern Montana on the Coram Experimental Forest. It has an east aspect, a slope averaging 55 percent, and an elevation of approximately 1,900 m. The primary ectomycorrhizal hosts are 250-year-old Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), western larch, subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), and Engelmann spruce (*Picea engelmannii* Parry). Lodgepole pine (*Pinus contorta* Dougl.), western hemlock, and western white pine (*Pinus monticola* Dougl.) occur occasionally.

Site 3 (DF-M) is a Douglas-fir climax in northwestern Montana on the Coram Experimental Forest. It has a south aspect, a slope averaging 27 percent, and an elevation of approximately 1,150 m. The primary ectomycorrhizal host is 250-year-old Douglas-fir. Western larch occur infrequently on this site.

Site 4 (WH-I) is a western hemlock climax in northern Idaho near the Priest River Experimental Forest. It has an east aspect, a slope averaging 10 percent, and an elevation of approximately 1,500 m. The primary ectomycorrhizal host is 250-year-old western hemlock. Western redcedar occur frequently on this site.

Site 5 (WWP-I) is a western hemlock climax in northern Idaho on the Deception Creek Experimental Forest. It has a northwest aspect, a slope averaging 5 percent, and an elevation of approximately 1,000 m. The primary ectomycorrhizal host is 250-year-old western white pine. Western hemlock, Douglas-fir, and grand fir (*Abies grandis* [Dougl.] Lindl.) occur occasionally.

Site 6 (GF-I) is a grand fir climax in northern Idaho on the Priest River Experimental Forest. It has a west aspect, a slope averaging 35 percent, and an elevation of approximately 1,200 m. The primary ectomycorrhizal hosts are 250-year-old western hemlock and Douglas-fir. Western white pine, grand fir, and western redcedar occur occasionally.

Site 7 (SAF-W) is a subalpine fir climax in northwestern Wyoming near Union Pass. It has a north aspect, a slope

averaging 20 percent, and an elevation of approximately 2,800 m. The primary ectomycorrhizal host is 165-year-old lodgepole pine. Subalpine fir and Engelmann spruce occur occasionally.

Site 8 (PP-W) is a ponderosa pine climax located in northeastern Washington near Spokane. It has a west aspect, a slope averaging 25 percent, and an elevation of approximately 700 m. The only ectomycorrhizal host is 200-year-old ponderosa pine (*Pinus ponderosa* Laws.).

Sample Sites, Second-Growth

Three of the six disturbed sites were chosen to provide a uniform habitat series (subalpine fir climax type) from a localized geographic area representative of a common commercial forest in the Inland Northwest. The other three were chosen to provide a comparison with drier conditions (Douglas-fir climax type) from the same geographic area (western Montana). To represent a variety of harvesting and natural stand situations frequently found in the Inland Northwest, treatments (disturbance type) were chosen to provide a variation in time since disturbance and in species dominance.

Site 9 (MIX-i) (i = intermediate-aged) is a subalpine fir climax type in western Montana adjacent to the Hungry Horse Reservoir. It has an east aspect, a slope averaging 40 percent, and an elevation of approximately 1,500 m. This is an old wildfire-impacted site that now supports a mixed-species, pole-sized, 80-year-old stand of primarily Douglas-fir. Subalpine fir is also abundant. Western white pine, grand fir, and birch (*Betula papyrifera* Marsh) occur occasionally.

Site 10 (LPP-i) is a Douglas-fir climax type in western Montana near Martin City. It has a west aspect, a slope averaging 5 percent, and an elevation of approximately 1,200 m. This is an unharvested site with the previous stand terminated by wildfire. The present stand is 50 years old. The primary ectomycorrhizal host is lodgepole pine. Douglas-fir occurs occasionally.

Site 11 (WL-y) (y = young-aged) is a subalpine fir climax type in western Montana adjacent to the Coram Experimental Forest. It has a north aspect, a slope averaging 15 percent, and an elevation of approximately 1,300 m. This is a harvested site (clearcut and broadcast burned) with a planted, 15-year-old stand of western larch. The primary ectomycorrhizal species is western larch. No other hosts occurred within the plot.

Site 12 (DF-i) is a Douglas-fir climax type in western Montana on the University of Montana's Lubrecht Experimental Forest. It has a west aspect, a slope averaging 10 percent, and an elevation of approximately 1,200 m. The site has an extensive harvesting history (intermittent selective cutting) and now has a mixed-size, intermediate-aged stand (60 to 120 years old) of nearly pure Douglas-fir. The primary ectomycorrhizal species is Douglas-fir. No other host occurred within the sampled area.

Site 13 (PP-i) is a Douglas-fir climax type in western Montana adjacent to the Hungry Horse Reservoir. It has a southwest aspect, a slope averaging 50 percent, and an elevation of approximately 1,300 m. This harvested site (partial cut with an underburn) now has a residual stand of ponderosa pine, 80 to 100 years old. The primary ectomycorrhizal host is ponderosa pine. An occasional, small Douglas-fir occurred within the sampled area.

Site 14 (LPP-y) is a subalpine fir climax type in western Montana near the town of Hungry Horse. It has a west aspect, a slope averaging 5 percent, and an elevation of approximately 1,200 m. The previous stand originated as a result of wildfire in 1929. The stand was harvested by clearcut (with an occasional seed tree). At the time of sampling there was a 15-year-old regenerating stand of lodgepole pine. Lodgepole pine was the only ectomycorrhizal host, with no other hosts in the sampled area.

Climate

Thirteen of these sites are representative of the typical Inland Northwestern climate characterized by cold wet winters and warm dry summers. The weather on these sites is generated primarily by Pacific frontal systems. Site 7 is located on the east side of the Continental Divide so is more often impacted by continental weather, including frequent summer rainfall generated by thunderstorm activity.

STUDY METHODS

Individual soil samples consisted of 10- by 38-cm soil cores (Jurgensen and others 1977) taken randomly, five from around each plot center, 10 plot centers scattered evenly (approximately 30-m spacing) over 1 ha of uniform conditions on each of the 14 study sites. Conditions evaluated for uniformity included slope, aspect, soils, disturbance, stocking, and understory vegetation. Samples were taken during late spring and early summer over several years (1978 to 1982) to obtain maximum ectomycorrhizal activity for each site (Harvey and others 1978). Each soil core was subdivided in the field into the following components or horizons: litter (O_1 horizon); humus (O_2 horizon); brown cubicle decayed soil wood, also referred to as the O_3 horizon (Harvey and others 1979); surface mineral soil (the first 5 cm); and the remaining mineral soil to a depth of 30 cm. Each fraction was hand-separated and placed in a plastic bag immediately after collection. Volume and depth occupied by each fraction was determined by measuring its depth in the undisturbed core.

In the laboratory, each soil fraction was shaken for approximately 5 minutes in a standard 2-mm soil sieve. Decayed wood, humus, or mineral aggregates were gently crumbed before sieving. Soil and root material greater than 2 mm were thoroughly washed in running water and examined microscopically for ectomycorrhizal short roots.

Active ectomycorrhizal root tips were counted with the aid of a dissecting microscope (10-50×). Each active tip was counted, even though in many cases it was part of a complex structure. No attempt was made to count or differentiate between root tips that were inactive and those that were dead. The criteria used for identifying "active" ectomycorrhizal root tips have been described (Harvey and others 1976).

RESULTS

The total quantity of soil organic materials varied significantly between sites (table 2). In general, high-productivity, old-growth ecosystems had high organic reserves. Low-productivity, old-growth and second-growth ecosystems, particularly harsh ones, had low organic reserves. The percentage distribution of organic fractions (litter, humus, decayed wood) making up the organic mantle also varied significantly. There were usually substantial deposits of decayed wood in the forest floor on most sites.

The total number of active ectomycorrhizal short root tips also varied significantly between sites (table 3). As with soil organic matter, the high-productivity, old-growth stands had high numbers of active short root tips, and the low-productivity, disturbed second-growth stands, particularly harsh ones, had low numbers of active tips. There were many significant differences in percentage distribution of active ectomycorrhizal short root tips among the soil fractions, both within and between sites. The most striking general trends were reduced short root tips in the deep mineral fraction and high numbers in the organic fractions, particularly humus and decayed wood. Only two sites had the highest number of active short root tips in a mineral fraction: old-growth ponderosa pine (site 8) and a 15-year-old stand of western larch (site 11). In both cases it was the shallow (first 5 cm) mineral horizon that contained most of the active tips (table 3).

Soil wood as an ectomycorrhizal substratum is particularly interesting. A number of factors indicate that the association between decayed wood and mycorrhizal activities may be of importance to host trees. Todd (1979) reports ectomycorrhizal fungi on Douglas-fir may be able to break down certain organic materials directly, a means for closed-cycle nutrient turnover. Selective concentration of mycorrhizal inoculum in soil wood has been reported (Kropp and Trappe 1982; Trappe 1965, 1962). Roots of nonconiferous vegetation are seldom observed in soil wood (Berntsen 1955; Harvey and others in press; Rowe 1955). The apparent ability of mycorrhizal fungi to detoxify soil phenolics (Zak 1971) may contribute to the ability of conifer roots to thrive in decayed wood on and in forest soils. Thus, soil wood provides a relatively competition-free site for the growth of conifer feeder roots. In turn, this provides a decided advantage to the conifers because they are able to use this high-moisture material during drought (Harvey and others 1978) and on dry sites (Harvey and others 1979). Also, it is now apparent that some higher plants have hydrotropic roots (Jaffe and others 1985). Thus, the moisture contained in soil wood may be the primary reason for the concentration of conifer roots therein.

Although the number of samples taken on most of the sites was not sufficient to show significant differences in distribution of ectomycorrhizal activities among organic matter classes (table 4), the trend toward low numbers of short roots in the highest organic content class (> 45 percent of the core) was striking. This was particularly evident in moderate- to low-productivity, old-growth stands and in second-growth sites. This trend is likely related to soil moisture availability. Periodic rainfall on these sites may not be enough to wet deep organic matter deposits sufficiently to maintain them above the permanent wilting point, particularly during the normally dry growing

Table 2—Quantity and distribution of soil organic components from plots sampled

Site number and acronym	Total organic matter in soil core ($\bar{x}$ L/core)	Distribution of organic matter in forest floor		
		Litter	Humus	Decayed wood
	Liters	- - - - - - - - - - *Percent* - - - - - - - - - -		
Old-growth[1]				
1(WH-M)	[2]0.82[w]	[3]12[a]	38[b]	51[b]
2(SAF-M)	.77[w]	7[a]	45[b]	48[b]
4(WH-I)	.54[x]	12[a]	30[b]	58[b]
3(DF-M)	.50[x]	6[a]	58[b]	35[b]
5(WWP-I)	.43[x]	30[a]	19[b]	51[a]
8(PP-W)	.38[x]	31[a]	68[b]	2[c]
6(GF-I)	.32[y]	25[a]	61[b]	14[a]
7(SAF-WY)	.15[z]	34[a]	52[b]	14[a]
Second-growth				
10(LPP-i)	.42[x]	19[a]	58[b]	23[a]
9(MIX-i)	.39[x]	19[a]	46[b]	36[ab]
11(WL-y)	.32[x]	21[a]	41[b]	39[ab]
12(DF-i)	.26[x]	22[a]	42[b]	35[ab]
13(PP-i)	.12[z]	27[a]	58[b]	15[a]
14(LPP-y)	.12[z]	46[a]	40[a]	14[b]

[1]See table 1 for explanation of abbreviations.

[2]Average includes all organic matter-containing strata. Differing letters indicate significant differences down column (w-z), $\alpha = 0.05$, ANOVA, Duncan's multiple range test.

[3]Differing letters (a-c) indicate significant differences ($\alpha = 0.05$) within treatments, between individual strata, detected by two-sided t-test on actual volume measurements.

Table 3—Number and distribution of active ectomycorrhizal root tips in soil strata; all samples taken during June to July peak activity period (Harvey and others 1978)

Site number and acronym	Number ectomycorrhizal roots ($\bar{x}$) all strata combined	Percent distribution of ectomycorrhizal root tips in				
		Litter	Humus	Decayed wood	Shallow mineral	Deep mineral
	No./liter	*Percent*				
Old-growth[1]						
5(WWP-I)	[2]120[w]	[3]10[ab]	57[b]	26[ab]	6[c]	1[d]
4(WH-I)	95[wx]	6[acde]	67[b]	16[cd]	8[d]	3[e]
1(WH-M)	93[wx]	6[a]	32[b]	51[bc]	10[ac]	1[a]
7(SAF-WY)	65[x]	6[a]	37[b]	28[a]	28[a]	1[a]
8(PP-W)	60[x]	1[a]	8[ac]	7[ac]	74[b]	10[c]
2(SAF-M)	21[y]	0	74[a]	19[bc]	6[b]	1[c]
6(GF-I)	14[y]	26[a]	13[a]	31[a]	20[a]	10[a]
3(DF-M)	11[y]	14[a]	30[a]	31[a]	21[a]	2[b]
Second-growth						
9(MIX-i)	49[x]	6[ac]	47[b]	35[abc]	10[c]	2[a]
10(LPP-i)	41[x]	10[ab]	15[a]	57[ab]	15[a]	2[b]
13(PP-i)	29[x]	0	25[a]	61[a]	11[a]	2[b]
14(LPP-y)	14[y]	0	36[a]	40[a]	21[a]	3[b]
11(WL-y)	7[z]	1[a]	23[a]	7[ab]	57[c]	11[b]
12(DF-i)	4[z]	20[a]	0	46[a]	33[a]	1[b]

[1]See table 1 for explanation of abbreviations.

[2]Differing letters indicate significant differences (α = 0.05) between sites, down column (w-z), and within strata and site, across (a-e), based on two-sided t-test of numbers of short root tips/liter.

[3]Ectomycorrhizal distribution in individual strata shown as a percentage of the total to facilitate between site comparisons.

seasons. Also, many sites with limited organic matter production have few substantial deposits accumulated, and those that do are likely to be disrupted by harvesting-related disturbances and natural wildfires. These results appear to support a management recommendation to maintain 2.4-3.6 tons/ha (10-15 tons/acre) (based on the 31 to 45 percent volume class) of woody residues to maintain soil organic reserves (Harvey and others 1981).

The concentration of ectomycorrhizal short root tips in shallow organic horizons (table 5) makes them extremely vulnerable to external perturbation. Even moderate physical disturbance or heating is likely to produce high mortality of short roots from nearby trees. Also, because it is now apparent that moisture laden with air pollutants (acid rain) can inhibit ectomycorrhizal activities (Reich and others 1985), their concentration in shallow horizons of Inland West forests may make them extremely vulnerable to air pollution damage. A shallow distribution of feeder roots from conifers has been noted (Fogel and Hunt 1979; Maser and Trappe 1984; Mikola and others 1966; Vogt and others 1981).

In the two instances reported here where the most ectomycorrhizal short root tips were not concentrated in the organic horizons (table 5, sites 8—old-growth ponderosa pine—and 11—second-growth western larch), they were concentrated in the topmost mineral layer (table 4). In one of these instances the dominant host (ponderosa pine) is a relatively deep-rooted species (Steinbrenner and Rediske 1964) growing on an extremely dry site where surface moisture is episodic and rare during the growing season. In the other instance, the dominant host was young western larch, a well-adapted pioneer species growing on a highly disturbed site with little surface organic matter present.

When soil organic matter content was grouped into volume classes for each site, numbers of active short root tips compared between classes showed no significant differences in distribution (table 4). However, a strong trend toward low numbers in the highest organic matter class (> 45 percent of the core) was evident. Also evident was the low percentage volume of the cores represented by organic fractions in all but the most productive ecosystems (table 2, table 4). When the comparison between organic classes was made on a larger sample base (150 cores), significant differences between classes within the Coram Experimental Forest sites in Montana for old-growth western hemlock, subalpine fir, and Douglas-fir (sites 1, 2, 3) were found (table 4).

A comparison of the distribution of ectomycorrhizal short root tips in all organic versus all mineral soil fractions (combined) showed a strong, frequently significant trend favoring organic fractions for all but the old-growth ponderosa pine and second-growth western larch sites (sites 8, 11) (table 5). A direct measurement of the depth of organic horizons (litter, humus, and decayed wood combined) showed the extreme shallow nature of organic

Table 4—Distribution of active ectomycorrhizal root tips (percentage of total in core) among organic matter (litter, humus, decayed wood) volume classes within and between sites; all samples taken during June to July peak activity period (Harvey and others 1978)

Site number and acronym	Mean percent of core organic	Organic matter volume class (percent)			
		0-15	16-30	31-45	>45
		Percent			
Old-growth[1]					
1(WH-M)	31	[2]13[a]	45[b]	23[c]	19[d]
2(SAF-M)	30	12[a]	57[b]	27[b]	5[a]
4(WH-I)	28	20	49	21	10
3(DF-M)	19	7[a]	36[b]	52[b]	4[c]
5(WWP-I)	17	12	20	40	27
8(PP-W)	15	39	44	17	0
6(GF-I)	13	44	43	13	0
7(SAF-WY)	6	58	0	42	0
Second-growth					
10(LPP-i)	17	57	12	31	0
9(MIX-i)	17	42	36	22	0
11(WL-y)	13	57	20	22	0
12(DF-i)	12	0	100	0	0
13(PP-i)	5	39	44	17	0
14(LPP-y)	5	100	0	0	0

[1]See table 1 for explanation of abbreviations.
[2]Within the sample used for these calculations (50 cores) no significant differences between treatments could be detected. However, on the three sites for which a larger sample was available (150 cores, Harvey and others 1981) significant differences were detected within the three sites (α = 0.05), two-sided t-test, differing letters indicate significant differences.

Table 5—Cumulative depth (centimeters) of organic soil strata and distribution of active ectomycorrhizal short roots in organic and mineral strata within and between sites; all samples taken during June to July peak activity period (Harvey and others 1978)

Site number and acronym	Cumulative depth/core of organic horizons	Total ectomycorrhizal short root tips in	
		Organic horizons (all)	Mineral horizons (all)
	cm	*Percent*	
Old-growth[1]			
1(WH-M)	3.8	89[a]	11[b]
2(SAF-M)	3.5	93[a]	7[b]
4(WH-I)	2.5	89[a]	11[b]
3(DF-M)	2.3	76[a]	24[a]
5(WWP-I)	2.0	93[a]	7[b]
8(PP-W)	1.7	16[a]	84[b]
6(GF-I)	1.5	70[a]	30[a]
7(SAF-WY)	.7	71[a]	29[a]
Second-growth			
10(LPP-i)	1.9	82[a]	18[a]
9(MIX-i)	1.8	89[a]	11[a]
11(WL-y)	1.5	31[a]	69[b]
12(DF-i)	1.2	66[a]	34[a]
13(PP-i)	.6	86[a]	14[a]
14(LPP-y)	.5	76[a]	24[a]

[1]See table 1 for explanation of abbreviations.
[2]Differing letters indicate significant differences (α = 0.05) within site, based on two-sided t-test of numbers of short root tips in combined strata.

horizons (less than 4 cm) in these forests, particularly low-productivity, harsh, or disturbed sites (table 5). The same trend was shown for percentage of the core (table 4) and total volume of sample (table 2) represented by organic horizons.

DISCUSSION

The tendency to accumulate soil organic matter in the mature, productive stands studied is probably a simple reflection of biomass production (table 2). However, the significantly greater accumulation on the western hemlock and subalpine fir sites in western Montana (sites 1 and 2) as compared to the western hemlock, white pine, and grand fir sites in northern Idaho that have higher productivity (sites 4, 5, 6—Pfister and others 1977) may indicate that the cool Montana climate slows decay of organic residues enough to offset higher biomass production in Idaho. The thin organic horizons on low to moderate productivity habitat series are commensurate with their production. The low to extremely low organic reserves (organic component volume by depth) on the variously disturbed sites likely reflect mixing, transport, and loss of the forest floor due to harvesting and site preparation (tables 2 and 5).

The distribution of soil organic components was highly variable in both combined total and individual quantity (table 2). However, substantial reserves of decayed wood were present in most of the old-growth stands, except those likely to have a frequent fire history (sites 6, 7, 8). Similarly, substantial reserves of decayed wood were present in most second-growth sites except where site preparation had been extensive (sites 13, 14). The relatively good balance between the long-lived organic components (wood and humus) on most of these sites may result from a usually infrequent or low-temperature fire history that allows production of the large woody residues required to produce soil-wood deposits.

Numbers of ectomycorrhizal short root tips also generally reflected site productivity, particularly of the undisturbed stands. On the second-growth sites, short root tip numbers were moderate in intermediate-aged stands and low in young stands (table 3). These numbers likely reflect the root density of host trees. However, reduced organic horizons may also be a contributing factor. Organic materials contain most of the soil nutrients (Harvey and others in press) and moisture (Barr 1930; Harvey and others 1978; Place 1950) and are a highly favorable substrate for ectomycorrhizal activities (Fogel and Hunt 1979; Harvey and others 1976, 1979, in press; Maser and Trappe 1984; Mikola and others 1966; Vogt and others 1981).

The highly significant distribution patterns of active ectomycorrhizal short root tips among the various soil components, both within and between sites (table 3), are likely brought about by the individual nature of these components as conditioned by the climate and fertility of the site (Harvey and others in press). For example, humus is an attractive substrate for feeder roots because of its high nutrient content, but its shallow depth limits moisture retention. On the other hand, soil wood is moderately supplied with nutrients but usually occurs in large enough volumes to be a significant source for moisture.

CONCLUSION AND APPLICATIONS

Perhaps the most striking effect (or lack thereof) of site or disturbance on numbers of ectomycorrhizal root tips, including differences in host species and time (age), was the generally similar distribution of ectomycorrhizal roots among organic versus mineral soil horizons. In most cases short root tips were concentrated in organic horizons. On the two sites where this did not occur, the forest floor was thin and root tips were most numerous in the surface mineral layer. Thus, the surface soils, particularly the organic horizons, were universally important for supporting this important feeder root activity on all 14 sites. This is a clear indication that management methods likely to impact soil surfaces, particularly mechanical site preparation and broadcast burning, should be applied with caution to minimize loss or disruption of surface soil horizons, organic and mineral. The extremely shallow distribution of most ectomycorrhizal activity (4 cm or less) emphasizes a critical need to protect this valuable resource.

REFERENCES

Barr, P. M. The effect of soil moisture of the establishment spruce reproduction in British Columbia. Bulletin 26. New Haven, CT: Yale University, School of Forestry; 1930. 57 p.

Bjorkman, E. Forest tree mycorrhizae—the conditions for its formation and the significance for the growth and afforestation. Plant and Soil. 32: 589-610; 1970.

Berntsen, C. M. Seedling distribution on a spruce-hemlock clearcut. Research Note PNW-119. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1955. 7 p.

Christy, J. E.; Sollins, P.; Trappe, J. M. First year survival of *Tsuga heterophylla* without mycorrhizae and subsequent ectomycorrhizal development on decaying logs and mineral soil. Canadian Journal of Botany. 60: 1601-1605; 1982.

Danielson, R. M. Ectomycorrhizal association in jack pine stands in northeastern Alberta. Canadian Journal of Botany. 62: 932-939; 1984.

Fogel, R.; Hunt, G. Fungal and arboreal biomass in a western Oregon Douglas-fir ecosystem: distribution patterns and turnover. Canadian Journal of Forest Research. 9: 245-256; 1979.

Hacskaylo, E. Dependence of mycorrhizal fungi on hosts. Bulletin of the Torrey Botanical Club. 100: 217-223; 1973.

Harvey, A. E.; Jurgensen, M. F.; Larsen, M. J. Seasonal distribution of ectomycorrhizae in a mature Douglas-fir/larch forest soil in western Montana. Forest Science. 24: 203-208; 1978.

Harvey, A. E.; Jurgensen, M. F.; Larsen, M. J. Organic reserves: importance to ectomycorrhizae in forest soils of western Montana. Forest Science. 27: 442-445; 1981.

Harvey, A. E.; Jurgensen, M. F.; Larsen, M. J.; Graham, R. T. Decaying organic materials and soil quality in the Inland Northwest: a management opportunity. General Technical Report. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; [in press].

Harvey. A. E.; Larsen, M. J.; Jurgensen, M. F. Distribution of ectomycorrhizae in a mature Douglas-fir/larch forest soil in western Montana. Forest Science. 22: 393-398; 1976.

Harvey, A. E.; Larsen, M. J.; Jurgensen, M. F. Comparative distribution of ectomycorrhizae in soils of three western Montana forest habitat types. Forest Science. 25: 350-358; 1979.

Herman, R. K. Growth and production of tree roots: a review. In: Marshal, J. K., ed. The belowground ecosystem: a synthesis of plant associated processes. New York: Dowden, Hutchinson, and Ross; 1977: 7-28.

Jaffe, M. J.; Takahashi, H.; Biro, R. L. A pea mutant for the study of hydrotropism in roots. Science. 230: 445-447; 1985.

Jurgensen, M. F.; Larsen, M. J.; Harvey, A. E. Effects of timber harvesting on soil biology. In: Proceedings, annual meeting, Society of American Foresters. Washington, DC: Society of American Foresters; 1977: 244-250.

Kropp, B. R.; Trappe, J. M. Ectomycorrhizal fungi of *Tsuga heterophylla*. Mycologia. 74: 479-478; 1982.

Larsen, M. J.; Harvey, A. E.; Jurgensen, M. F. Residue decay processes and associated environmental functions in Northern Rocky Mountain forests. In: Environmental consequences of timber harvesting. General Technical Report INT-90. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980: 157-174.

Maser, Chris; Trappe, J. M., tech. eds. The seen and unseen world of the fallen tree. General Technical Report PNW-164. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1984. 56 p.

McFee, W. W.; Stone, E. L. The persistence of decaying wood in the humus layers of northern forests. Soil Science Society of America Proceedings. 30: 513-516; 1966.

McMinn, R. G. Characteristics of Douglas-fir root systems. Canadian Journal of Botany. 11: 105-122; 1963.

Meyer, F. H. Distribution of ectomycorrhizae in native and man-made forests. In: Marks, G. C.; Koylowski, F. F. Ectomycorrhizae: their ecology and physiology. New York: Academic Press; 1973: 79-105.

Mikola, P.; Hahl, S.; Tornianen, E. Vertical distribution of mycorrhizae in pine forests with spruce undergrowth. Annals of Botany Fenn. 3: 406-409; 1966.

Park, J. L.; Linderman, R. G.; Trappe, J. M. Effects of forest litter on mycorrhizae development and growth of Douglas-fir and western red cedar seedlings. Canadian Journal of Forest Research. 13: 666-671; 1983.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 172 p.

Pilz, D. P.; Perry, D. A. Impact of clearcutting and slash burning on ectomycorrhizal associations of Douglas-fir seedlings. Canadian Journal of Forest Research. 14: 94-100; 1984.

Place, I. C. M. Comparative moisture regimes of humus and rotten wood. Silviculture Leaflet 37. Ottawa, ON: Canadian Department of Research and Development, Forest Research Division; 1950. 2 p.

Reich, P. B.; Schoettle, A. W.; Stroo, H. F.; Troiano, J.; Amundson, R. G. Effects of 0_3, $S0_2$, and acid rain on mycorrhizal infection in northern red oak seedlings. Canadian Journal of Botany. 63: 2049-2055; 1985.

Rowe, J. S. Factors influencing white spruce reproduction in Manitoba and Saskatchewan. Technical Note 3. Winnipeg, MB: Canadian Department of Northern Affairs and National Resources, Forestry Branch, Forest Research Division; 1955. 27 p.

Steinbrenner, E. C.; Rediske, J. H. Growth of ponderosa pine and Douglas-fir in a controlled environment. Paper Number 1. Centralia, WA: Weyerhaeuser Forest; 1964. 31 p.

Todd, A. W. Decomposition of selected soil organic matter components by Douglas-fir ectomycorrhizal associations. In: Abstracts of the 4th North American conference on mycorrhizae. Fort Collins, CO: Colorado State University; 1979.

Trappe, J. M. Fungus associates of ectotrophic mycorrhizae. Botanical Research. 29: 538-606; 1962.

Trappe, J. M. Tuberculate mycorrhizae of Douglas-fir. Forest Science. 11: 27-32; 1965.

Trappe, J. M.; Strand, R. F. Mycorrhizal deficiency in a Douglas-fir region nursery. Forest Science. 15: 381-389; 1969.

Vogt, K. A.; Edmonds, R. L.; Grier, C. C. Seasonal changes in biomass and vertical distribution of mycorrhizal and fibrous-textured conifer fine roots in 23- and 180-year-old subalpine *Abies amabalis* stands. Canadian Journal of Forest Research. 11: 223-229; 1981.

Vozzo, J. A.; Hacskaylo, E. Inoculation of *Pinus caribaea* with ectomycorrhizal fungi in Puerto Rico. Forest Science. 17: 239-245; 1971.

Zak, B. Detoxication of autoclaved soil by a mycorrhizal fungus. Research Note PNW-159. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1971. 4 p

☆ U.S. GOVERNMENT PRINTING OFFICE 1986—791-032/41,033 REGION NO. 10

Harvey, Alan E.; Jurgensen, Martin F.; Larsen, Michael J.; Schlieter, Joyce A. Distribution of active ectomycorrhizal short roots in forest soils of the Inland Northwest: effects of site and disturbance. Research Paper INT-374. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1986. 8 p.

Approximately 75 percent of ectomycorrhizal activities that occurred in soils from eight undisturbed and six variously disturbed sites occurred in shallow organic horizons. These horizons represented only the first 4 cm of soil depth. This disproportionate participation of surface organic materials emphasizes a need to conserve them in forested ecosystems of the Inland West.

KEYWORDS: soil microbial activity, soil quality, soil productivity, soil management, fire management, site preparation, site protection

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-375

February 1987

Components of Adaptive Variation in *Pinus contorta* from the Inland Northwest

G. E. Rehfeldt

CLEMSON UNIVERSITY
MAY 27 '88
PUBLIC DOCUMENTS

THE AUTHOR

G. E. REHFELDT is a plant geneticist at the Intermountain Research Station's Forestry Sciences Laboratory in Moscow, ID. He has been studying the ecological and quantitative genetics of Rocky Mountain conifers since 1968.

RESEARCH SUMMARY

Genetic variation among 83 populations of *Pinus contorta* from the Northern Rocky Mountains of the United States was studied with 7-year-old trees planted in three contrasting environments. Analyses of nine traits reflected adaptation to biotic and abiotic environments and revealed clinal patterns of differentiation that were elevationally steep but geographically gentle. In particular, populations from relatively mild environments had the highest growth potential but suffered the most snow damage when planted at high elevations. Populations from high elevations were most susceptible to needle cast when transferred to low elevation. And populations transferred the greatest geographic distances suffered the most from infestations of mites. Regression models present adaptive landscapes that mirror elevational and geographic gradients in climate.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Components of Adaptive Variation in *Pinus contorta* from the Inland Northwest

G. E. Rehfeldt

INTRODUCTION

Adaptive differentiation is discernible either directly as differential fitness in contrasting environments or indirectly as genetic responses that parallel environmental gradients. In *Pinus contorta* Dougl., for example, four geographic races are distinguished both morphologically (Critchfield 1957) and enzymatically (Wheeler and Guries 1982). Critchfield (1980) reviewed numerous studies that provide direct and indirect evidence of differential adaptation of races to climates as diverse as those of the northern Pacific Coast, the Sierra Nevada, the interior Rocky Mountains, and the Canadian subarctic.

In *P. contorta* spp. *latifolia*, the subject of this paper, genetic variation among populations is pronounced. Canadian populations, native to a region of dissected plateaus, are arranged along gentle clines that follow climatic gradients across 18° of latitude from the Yukon to southern British Columbia (Hagner 1970; Lindgren and others 1976; Ying and others 1985). In the mountains of Idaho (Rehfeldt 1983a), Utah (Rehfeldt 1985a), and Oregon (Stoneman 1985), population differentiation occurs along steep elevational clines that parallel the environmental changes associated with altitude. Whether geographic or elevational clines predominate, populations from mild environments express a high innate growth potential and low cold hardiness, while those from severe environments display a low growth potential and high hardiness.

Adaptive clines result from environmental selection of phenotypes that, for long-lived trees, develop in environments of extreme temporal heterogeneity. Adaptedness, therefore, has many component traits. A consideration of the interrelationships among components inspired Lande (1982) to argue that negative genetic correlations are often obscured phenotypically but commonly set the limits on microevolution. In trees, for example, negative genetic correlations relate growth potential and cold hardiness within families of both *Pseudotsuga menziesii* (Mirb.) Franco and *P. contorta* (Rehfeldt 1984). This means that an assessment of adaptive differentiation requires an understanding of component traits and their interrelations. Lande (1982) stressed that this understanding is particularly necessary for fields such as forestry where the traits of agronomic importance—growth and yield—are also major components of fitness.

The present study of *Pinus contorta* assesses genetic variability among populations, relates genetic variability to adaptive differentiation, and presents adaptive landscapes for the Inland Northwest.

DISTRIBUTION, ECOLOGY, AND DEMOGRAPHY

Adaptive variation must be interpreted according to the spatial environmental heterogeneity within the region of study (fig. 1). The climate of the Inland Northwest varies from the continental in the east to that with a coastal component in the west (Daubenmire and Daubenmire 1968; Pfister and others 1977). This general trend is reflected not only in gradients of temperature and precipitation (fig. 2), but also in the composition and distribution of plant communities (Daubenmire and Daubenmire 1968; Pfister and others 1977; Steele and others 1981). Superimposed on general climatic gradients are the topographic microclimates associated with mountainous terrain. Extreme environmental heterogeneity thus develops from a climatic transition that occurs across a series of rugged mountain ranges.

In the Rocky Mountains, *P. contorta* displays such a broad ecological distribution that it is capable of growing in almost any forest environment (Pfister and Daubenmire 1973). As an early successional species, the pine is common in a variety of plant communities that include associations dominated at maturity by *Tsuga heterophylla* (Raf.) Sarg. on mesic sites, *Pseudotsuga menziesii* (Mirb.) Franco on dry sites, and *Abies lasiocarpa* (Hook.) Nutt. on cold sites (Daubenmire and Daubenmire 1968; Pfister and others 1977; Steele and others 1981). The species forms large continuous populations on subalpine sites at elevations up to 3,000 m and in frost pockets on valley floors as low as 600 m.

Natural populations of *P. contorta* tend to be established in cycles (Lotan and others 1985). Greatly simplified, these cycles involve (1) wildfire, (2) profuse even-aged reproduction of as much as 500,000 seedlings/ha from either open or serotinous cones (Tackle 1959), (3) intense natural thinning, which can leave as few as 1,000 trees/ha by age 80 (Tackle 1959; Benson 1982; Vyse and Navratil 1985), and (4) epidemics of the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (Amman and others 1973; Shrimpton and Thomson 1983), which supplement the competitive mortality to provide the fuel for (5) wildfire.

These demographic cycles have pronounced effects on the genetics of populations. First, adaptive traits will include all traits that either directly or indirectly influence the expression of growth potential and thereby determine which trees are living when fires occur. And second, populations are frequently established on the same sites on

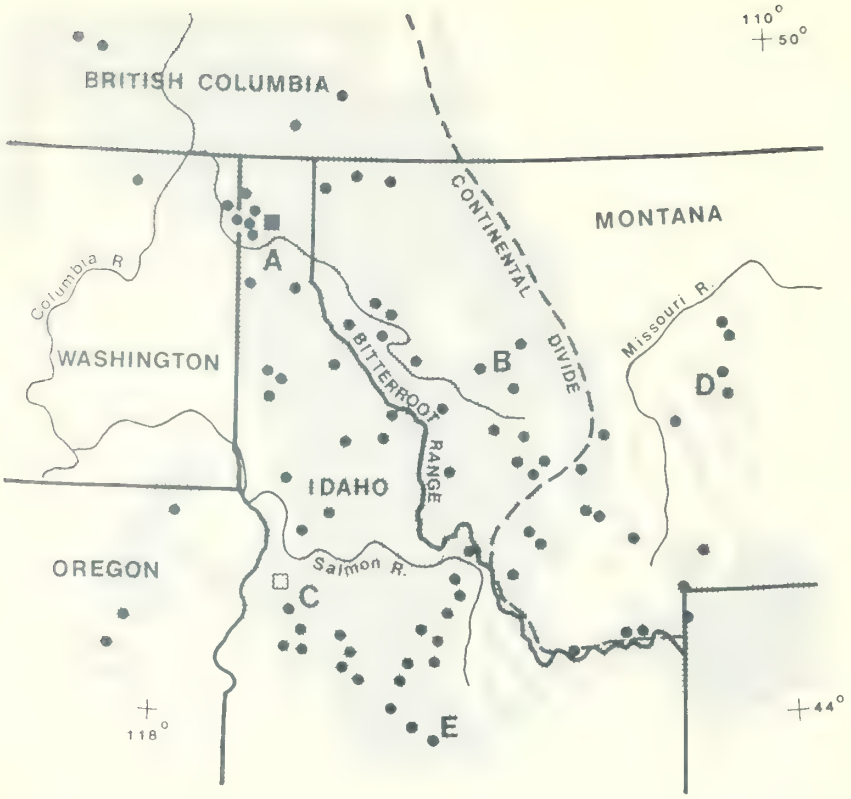


Figure 1—Distribution (shading) of *Pinus contorta* (from Little 1971) within the Northern Rocky Mountains, and location of populations sampled (dots). Letters A to E locate the elevational clines of figure 3. □ = Lost Valley, ■ = PREF.

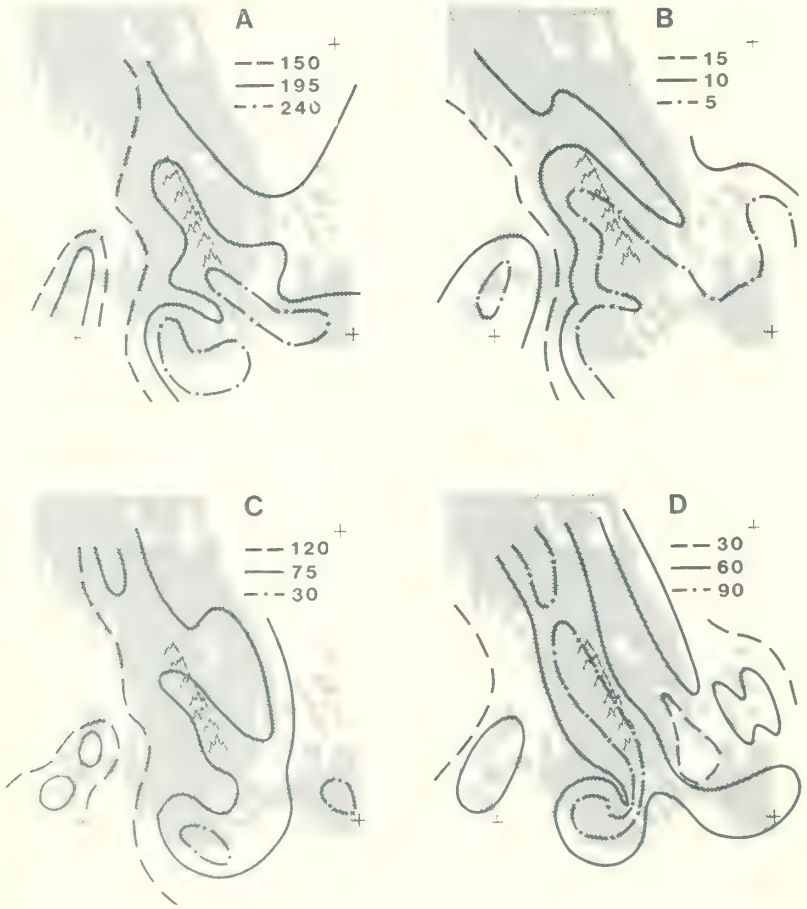


Figure 2—Climatic isopleths in relation to the distribution of the species (shading) and location of the Bitterroot Range (symbols) for (A) mean annual number of days with temperatures lower than 0 °C, (B) mean annual days with temperatures greater than 30 °C, (C) average annual frost-free period, and (D) mean annual precipitation (cm) (U.S. Department of Commerce 1968).

which ancestral populations grew, and therefore coadaptive complexes of traits can readily be perpetuated once such complexes arise.

Thus, a broad ecological distribution, a unique cycle of population establishment, and occupancy of an extremely heterogeneous environment make *P. contorta* an ideal species for studying adaptedness, the degree by which individuals are physiologically attuned to their environment.

MATERIALS AND METHODS

Genetic variation was studied in seedlings from 83 populations (fig. 1) that represented the geographic and ecological distribution of *P. contorta* in the Northern Rocky Mountains. Populations ranged in elevation from 640 to 2,700 m and represented habitat types as diverse as the *Tsuga heterophylla/Pachistima myrsinites* on moist sites and the *Abies lasiocarpa/Vaccinium scoparium* in subalpine communities.

Because of pronounced genetic heterogeneity within populations (Rehfeldt 1985b; Ying and others 1985), cone collections were conducted in a manner to assure that subsequent seedling populations would represent a large number of parental trees. Thus, about 250 wind-pollinated cones, each containing about 25 viable seeds, were selected from several squirrel caches in each population. Genetic diversity was further assured by selecting a variety of cone morphologies, sizes, and colors from each cache.

Seedlings were grown for 6 months in plastic containers (65 cm^3) in a shadehouse at Moscow, ID (lat. 48.5° N., long. 116.7° W.). In the fall, seedlings were planted at three locations (fig. 1): at 640 m and 1,500 m elevation on the Priest River Experimental Forest (PREF), and at 1,500 m in Lost Valley. The experimental design consisted of a random allocation of linear seedling plots within rows of a rectangular planting. A plot comprised eight seedlings from each population. Nine plots represented each population at PREF sites, and six plots represented each population at Lost Valley. Thus, 72 seedlings represented each population at both PREF sites while 48 represented each population at Lost Valley. The spacing of seedlings within and between rows was: 0.5 m and 1 m, respectively, at PREF 640; 0.5 m and 0.5 m at PREF 1,500; and 1 m and 1 m at Lost Valley.

Intensive culture at PREF included control of competing vegetation, gophers, and white grubs. The site at 640 m was irrigated once during years 2 and 3. No control of extraneous environmental effects was provided at Lost Valley. Variable cultural regimes and spacing of trees in different physical environments sample a range of conditions under which populations exist naturally. Survival was 76 percent at PREF 640, 83 percent at PREF 1,500, and 65 percent at Lost Valley.

Periodic measurements or scores provided the following variables:

1. Mean height for each plot after 3 years.
2. Height of individual trees after 7 years.
3. Adjusted height: the 7-year height of individual trees adjusted by regression on 5-year height.
4. Late growth of trees at PREF: the amount of the 7-year, predetermined shoot that elongated after the date when the uppermost leaves of the shortest trees were approximately 2 cm long (June 4 at 640 m; July 3 at 1,500 m).
5. Needle cast: the proportion of 6-year leaves of individual trees at PREF 640 that were infected with *Lophodermella concolor* (Dearn.) Darker, scored in July of year 7 with values of 1 to 5, which coded <5 percent, 25 percent, 50 percent, 75 percent, or >95 percent infected leaves.
6. Mites: the presence or absence of *Trisetacus campnodus* Keifer (Hunt 1981) on 7-year shoots of individual trees at PREF 640.
7. Shoot borers: the presence or absence of *Eucosma sonomana* Kearfott on the 7-year shoots of individual trees at PREF 640.
8. Frost injury: presence or absence of spring frost injury to the developing 7-year shoot at PREF 640.
9. Snow damage: scored in the spring of year 7 as the presence or absence of basal injuries of individual trees at PREF 1,500 sufficient to expose the inner bark.

Population differentiation was assessed with data from individual trees for all variables except snow damage, frost injury, mites, and shoot borers, for which the proportion of injured trees in each plot was analyzed. Allometric traits were transformed to logarithms because variances were proportional to the square of mean values. Scores of needle cast were transformed to $\sqrt{X}$ to normalize distributions. Three-year height was not subjected to rigorous analysis but was used only for correlation.

Statistical analyses followed a general model of unweighted means (Steel and Torrie 1960):

$$Y_{ijkl} = \mu + s_i + p_j + sp_{ij} + d_{k(ij)} + e$$

where Y_{ijkl} = the performance of the lth tree of the kth plot of the jth population at the ith planting site, μ = the overall mean, s = the effect of the planting site, p = the effect of the population, sp = the interaction of sites and populations, d = the effect of plots within populations and sites, and e = the residual.

Multiple regression models were used to relate genetic variation to the elevation and geographic location of the seed source. Independent variables included elevation, latitude, longitude, northwest departure, southwest departure, and their squares. Northwest and southwest departures were derived by rotating the grid of latitude and longitude by 45°. Geographic variables were nested within four geographic regions that had proven useful in previous analyses (Rehfeldt 1980; Rehfeldt and Wykoff 1981): Idaho north or south of the Salmon River, and Montana east or west of the Continental Divide (fig. 1). However, the geographic regions were not represented by dummy variables because such variables force continuous genetic variation to be described discontinuously. Interactions of elevation and geographic variables were not considered because preliminary analyses indicated that the effects of elevation could be described by similar regression coefficients in all geographic regions. Thus, 34 independent variables were screened by a stepwise regression model for maximizing R^2 (SAS 1982) according to the general model:

$$Y_i = \beta_0 + \beta_1 E_i + \beta_2 E_i^2 + \sum_{jk} \gamma_{jk} X_{ijk} + \sum_{jk} \delta_{jk} X_{ijk}^2$$

where Y_i is the performance of population i; E_i is the elevation of population i; X_{ijk} is geographic variable k for population i in geographic region j; and β_0, β_1, β_2, γ_{jk}, and δ_{jk} are regression coefficients, $j = 1 \ldots 4$, $k = 1 \ldots 4$.

Adequacy of a model was judged according to the goodness of fit (R^2), residual variance ($s_{y \cdot x}$), and patterns displayed by residuals (Draper and Smith 1981).

RESULTS

Environmentally diverse planting sites strongly influenced growth and development of seedlings (table 1). While the average tree at PREF 640 was 106 cm tall, that at PREF 1,500 and Lost Valley was only 76 cm and 62 cm, respectively. Values for adjusted height imply that, even if all trees had been the same height at age 5, by age 7 those at PREF 640 would still have been about 10 cm taller than trees on the other sites. Main effects of test environments are also expressed by the occurrence of snow damage only at high elevations and by the relatively high incidence of needle cast, shoot borers, and frost injuries at low elevation. Environmental effects on late growth also were pronounced; similar stages of shoot elongation occurred about 1 month later at PREF 1,500 than at PREF 640.

In these heterogeneous planting environments, mean differences between populations were statistically significant for all traits except adjusted height (table 1). Pronounced effects of populations were associated with mean differences as large as 55 cm in 7-year height, 5 cm in late growth, 78 percent in leaves infected with needle cast, and 65 percent in number of trees exhibiting snow damage. Weak effects of populations were evident for mites, spring frost damage, and shoot borers largely because of low incidence for each variable. Thus, mites occurred on only 10 percent of the trees, but as many as 33 percent of the trees from one population were infested. The proportion of trees damaged from a spring frost was only 2 percent, but mean values for populations ranged up to 11 percent. And the incidence of shoot borers for most populations was incidental <5 percent), but 19 percent of the trees were injured in one of the British Columbia populations.

Interactions of provenances and test environments were also significant for all variables measured on more than one site (table 1). Interactions for late growth and 7-year height obviously represented a scale effect because simple correlations of population means for the same variable at different sites ranged from 0.80 to 0.92. The interaction for adjusted height most likely resulted from various maladaptations that have accumulated between ages 5 and 7 and have differentially affected the height of populations at each planting site. This interaction is clarified by subsequent analyses that consider adjusted height at each test site as separate traits.

Simple correlations (table 2) describe a relationship between the height of populations at ages 3 and 7 that is nearly perfect ($r = 0.94$). Other extremely strong correlations (table 2) show that the tallest populations at ages 3 and 7 also (1) produced the most 7-year elongation after midsummer (late growth) regardless of test site, (2) grew the most from a common height at age 5 when planted at low elevation, (3) suffered little needle cast and few injuries from spring frost when planted at low elevation, but (4) were the most susceptible to snow damage at high elevations. Populations that were short also had little late growth, suffered the least snow damage, but were most susceptible to needle cast at low elevations. Table 3 illustrates that the tallest populations suffered the most injury from autumn freezing tests (Rehfeldt 1980) and displayed the greatest growth and longest duration of elongation in studies of the periodicity of shoot elongation involving 2-year-old trees (Rehfeldt and Wykoff 1981).

Regression models for relating variation among populations to the elevation and geographic location of the seed source were not only statistically significant for all variables but also accounted for over 80 percent of the genetic variance in five variables (table 4). These models, however, included between 10 and 20 independent variables and were therefore subject to overfitting, the fitting of variables to individual samples rather than to the group (Draper and Smith 1981). Consequently, biological significance of the results is judged with respect to the least significant difference (Steel and Torrie 1960) at the 95 percent level of probability, *lsd* (.05), calculated from analyses of variance and presented in figure 3.

Table 1—Results of analyses of variance expressed as intraclass correlations. σ^2_E, σ^2_P, σ^2_{PE}, $\sigma^2_{D(P)}$, and σ^2_W are variance components associated with the effects of environments and populations, interaction, plots in populations, and error variance within plots. σ^2_T is the sum of all components

Variable	σ^2_E/σ^2_T	σ^2_P/σ^2_T	σ^2_{PE}/σ^2_T	$\sigma^2_{D(P)}/\sigma^2_T$	σ^2_W/σ^2_T
7-year height	0.39**	0.16**	0.03**	0.12**	0.30
Adjusted height	.72**	−.00	.12**	.05**	.11
Late growth	.05**	.29**	.20**	.05**	.41
Needle cast		.52**		.07**	.41
Mites		.05**		.95	
Shoot borer		.05**		.95	
Spring frost injury		.09**		.91	
Snow damage		.40**		.60	

**Statistical significance of F-value at the 1 percent level of probability.

Table 2—Matrix of simple correlation coefficients among mean values for 83 populations. Absolute values greater than 0.21 or 0.26 are statistically significant at the 5 and 1 percent levels of probability, respectively

Variable	Codes	HT7	AH1	AH2	AH3	LG	NC	M	SB	FI	SD
3-year height	HT3	0.94	0.82	−0.40	0.14	0.88	−0.84	−0.29	0.36	−0.43	0.74
7-year height	HT7		.89	−.26	.29	.94	−.85	−.26	.44	−.41	.72
Adjusted height											
PREF 640	AH1			−.19	.29	.92	−.93	−.26	.41	−.43	.78
PREF 1,500	AH2				+.00	−.13	.31	.24	.02	.13	−.33
Lost Valley	AH3					.25	−.17	.04	.14	−.06	.16
Late growth	LG						−.86	−.20	.45	−.41	.68
Needle cast	NC							.29	−.41	.39	−.76
Mites	M								.09	.14	−.30
Shoot borer	SB									−.12	.23
Frost injury	FI										−.34
Snow damage	SD										

Table 3—Correlation of 30 population means from field tests with laboratory tests of freezing injury (Rehfeldt 1980) and greenhouse evaluations of the periodicity of shoot elongation (Rehfeldt and Wykoff 1981). Coefficients of absolute value greater than 0.35 and 0.45 are statistically significant at the 5 and 1 percent levels, respectively

Variable	Freezing injury	Shoot elongation			
		Amount	Initiation	Rate	Duration	Cessation
3-year height	0.82	0.81	−0.19	0.67	0.79	0.79
7-year height	.81	.80	−.22	.63	.82	.81
Adjusted height						
PREF 640	.75	.62	−.22	.40	.81	.80
PREF 1,500	.32	−.19	−.30	−.25	−.22	−.27
Lost Valley	.09	.17	.25	.16	.14	.18
Late growth	.85	.80	−.26	.61	.81	.80
Needle cast	−.77	−.59	.18	−.42	−.76	−.76
Mites	−.01	−.14	.29	−.03	−.11	−.06
Shoot borer	−.43	.19	−.20	.06	.42	.41
Spring frost injury	.27	−.55	.30	−.48	−.53	−.50
Snow damage	.52	.59	−.17	.47	.69	.69

Table 4—Results of stepwise multiple regression analyses presented as standard errors (s) and coefficients of determination (R^2)

Dependent variable	Independent variables	R^2	s
	Number		
7-year height	10	0.89**	0.0654
Adjusted height			
PREF 640	13	.86**	.0350
PREF 1,500	15	.50**	.0197
Lost Valley	16	.45**	.0273
Late growth	13	.91**	.1878
Needle cast	13	.88**	.1113
Mites	20	.41**	.0536
Shoot borers	13	.41**	.0258
Spring frost injury	15	.40**	.0203
Snow damage	18	.80**	.0740

**Statistical significance at the 1 percent level.

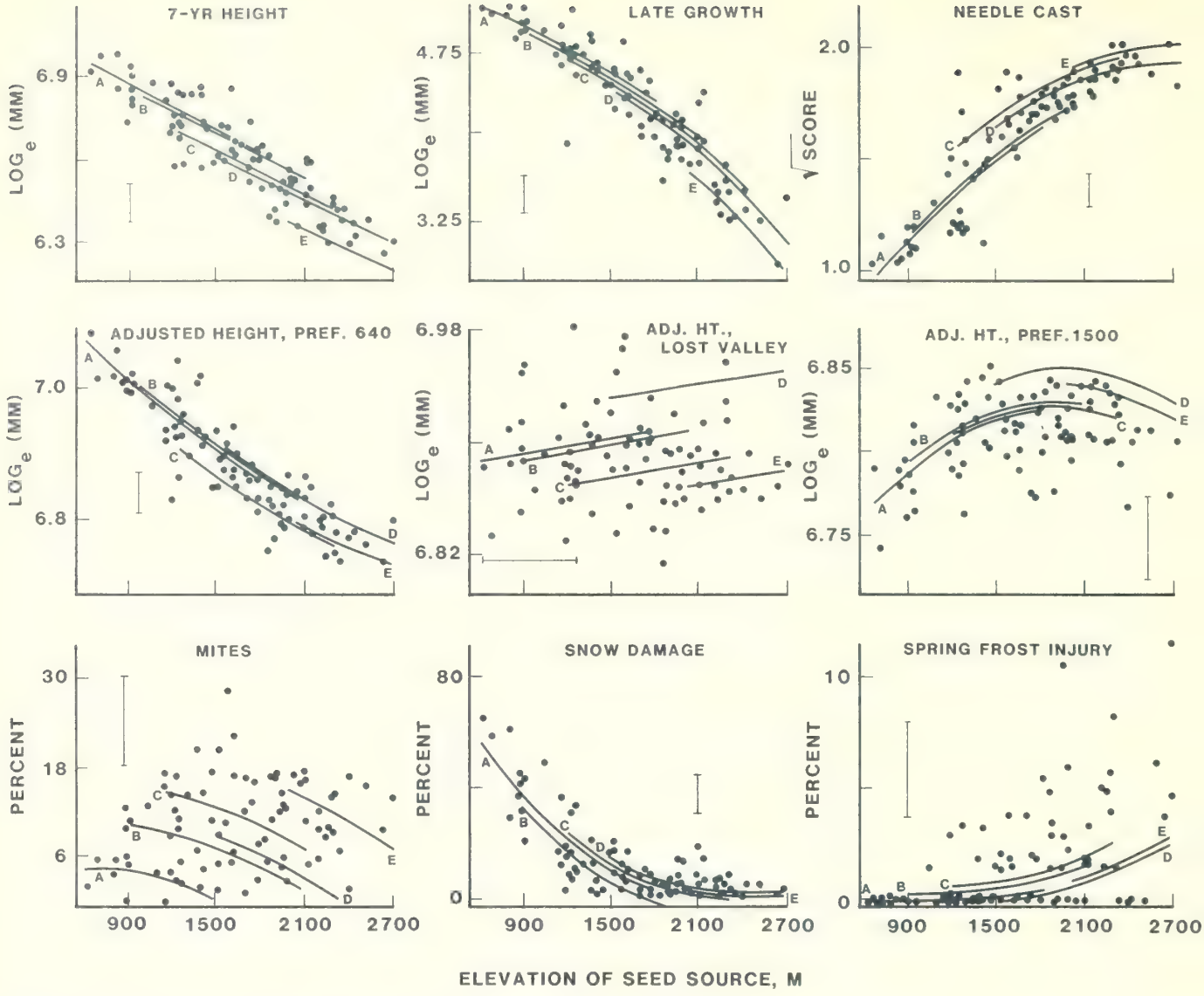


Figure 3—Population means for six variables plotted by elevation of the seed source. Localities A to E are keyed to figure 1. The length of each regression line reflects elevational distributions at each locality. Brackets quantify *lsd* (0.05).

Figure 3 illustrates steep elevational clines for five variables. The higher the elevation of the seed source, the lower the 7-year height, the less the late growth, the greater the needle cast, and the less the snow damage. And, if all trees at PREF 640 had been the same height after 5 years, the height of populations at age 7 still would have been distributed according to elevational clines. Moreover, the model for adjusted height at PREF 1,500 (fig. 3) shows that populations from about the same elevation as the 1,500-m planting site have grown the most from a common height at age 5.

Elevational clines for mites, spring frost injury, and adjusted height at Lost Valley are so gentle that they are biologically insignificant. The model for shoot borers is not presented because it was fit primarily to the population for which 19 percent of the trees were infested.

Because elevation and geography are not independent of each other, geographic patterns of variation can be described either as (1) performance at a constant elevation or (2) performance at a base elevation, the lowest elevation that the species occurs at a given locality. Figure 3 shows that populations at the base elevations for localities A and E, for example, differ tremendously for most traits. But most of these differences arise because populations at base elevations occupy much different positions along the elevational cline (fig. 3).

Nevertheless, geographic variation at a constant elevation was significant for five of the variables (fig. 3). In all cases, however, the differences barely exceeded *lsd* (.05). Therefore, geographic clines for a constant elevation can be described by the relatively gentle clines of figure 4. In this figure, geographic patterns are depicted by isopleths

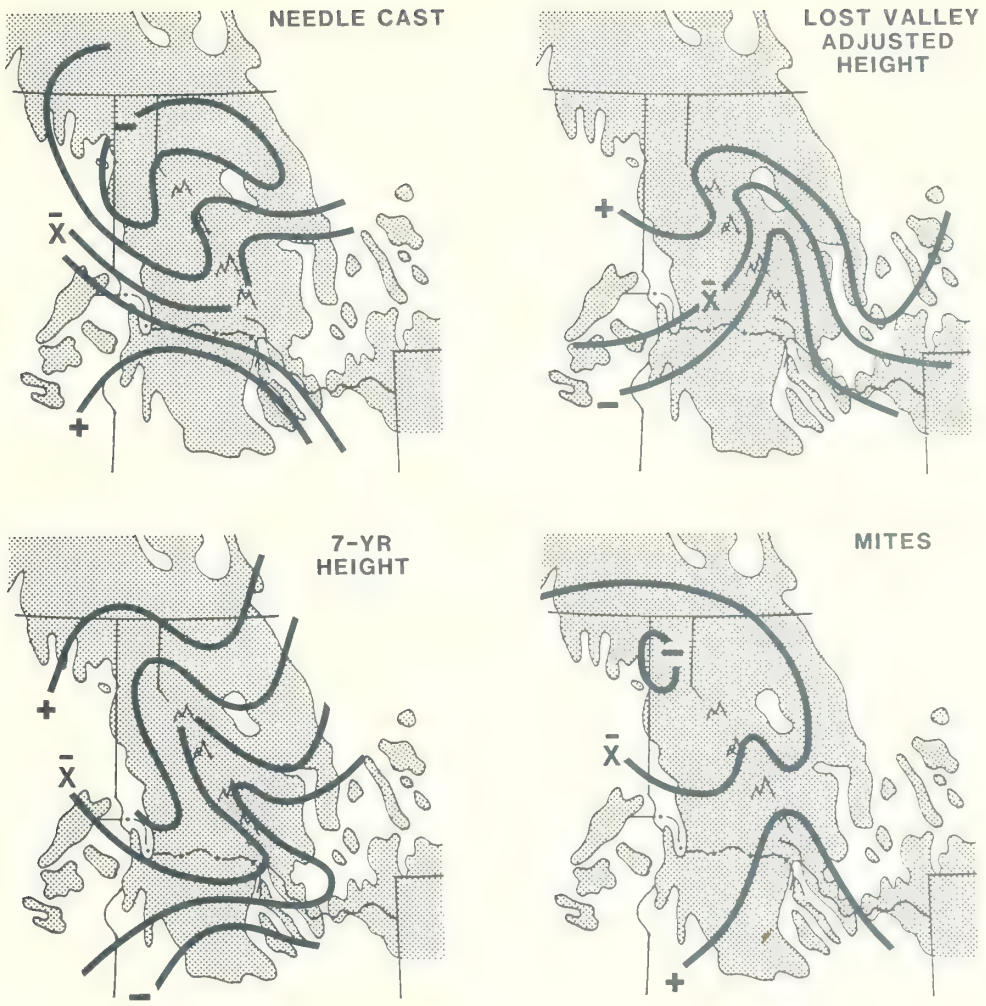


Figure 4—Geographic patterns that are independent of elevation as predicted by regression models. Patterns are relative to the distribution of the species (shading), the Bitterroot Range, and the Salmon River. Isopleths are positioned relative to the mean value ($\bar{x}$) with an interval scaled to ½*lsd* (0.05).

of relatively equal predicted performance for the mean elevation (1,625 m). Contouring was begun with the mean value, and the interval between isopleths was scaled to ½*lsd* (.05). Thus, populations separated by two isopleths are expected to differ at about the 95 percent level of probability. The pattern for late growth duplicates that of 7-year height and is not presented.

When comparing populations from the same elevation, those from the north were the tallest and had the most late growth; populations from central Idaho were the shortest and exhibited little late growth. The percentage of trees infected with needle cast or infested with mites was directly related to the geographic distance that the seed was transferred to the planting site. Populations of highest adjusted heights at Lost Valley (1,500 m) tended to be from the north where growth potentials were highest.

DISCUSSION

The results illustrate differentiation of populations for numerous traits which together determine adaptedness, the degree by which populations are physiologically attuned to their environment. Genetic differentiation was readily detected experimentally, and patterns of genetic variation were closely associated with the elevation and geographic location of the seed source. Pronounced clines tend to typify genetic differentiation in montane populations of *P. contorta* spp. *latifolia* (Ying and others 1985; Rehfeldt 1983a, 1985a; Stoneman 1985).

That the clines reflect adaptation to natural environments is demonstrated both directly, as differential fitnes in contrasting environments, and indirectly, as genetic responses that parallel environmental gradients. Thus, indirect support is provided by the steep elevational clines

that parallel a change of 80 days in the frost-free period across 1,000 m elevation (Baker 1944). Likewise, the geographic patterns of variation illustrated in figure 4 unmistakably parallel geographic climatic patterns of figure 2. As a result, geographic patterns of genetic variation are strongly influenced by the Bitterroot Range and Salmon River Drainage.

Thus, populations from mild environments exhibit a high innate growth potential that develops from a long duration of elongation. Those from severe environments exhibit the low growth potential and short duration of elongation expected in populations adapted to a short growing season. For these clines to reflect adaptive differentiation is unquestionable; rejection of such indirect evidence requires acceptance of an untenably improbable alternative: that the systematic patterns have developed randomly.

Although direct evidence for adaptive clines ultimately resides with the survival or death of individuals, the demographic cycles of population establishment in *P. contorta* endow an adaptive value to all traits that condition growth and development in a particular environment. Thus, direct support of adaptive clines is provided by the differential incidence of snow damage, needle cast, and mites, as well as by differences in growth potential itself. At high elevations, such as PREF 1,500 where snow accumulations commonly exceed 3 m, populations from mild environments suffered considerable damage from the snow. Mean differences calculated within populations showed that the 7-year shoot elongation of trees damaged by the snow was 22 percent less than that of trees not damaged. Consequently, damaged trees had an adjusted height that was 5 percent less than undamaged trees from the same population.

Similarly, needle cast is a disease most common in relatively humid valleys (Krebill 1975), and therefore, populations native to either high elevations or arid climates are rarely exposed to the disease. The present data, as well as those of Hoff (1985), show that populations from either high elevations or southern latitudes are much more susceptible to needle cast than populations from low elevations. Mean differences within populations depict a tremendous reduction in 7-year height for diseased trees. For each increase in the damage score of one unit—an increase of approximately 25 percent in infected leaves per tree—7-year height was reduced about 4 percent. This means that reductions in 7-year height between uninfected and severely infected trees from the same population would amount to nearly 17 percent. This reduction accrued largely from a corresponding reduction of 34 percent in shoot elongation during year 7.

Mites receive no recognition in pest surveys for Rocky Mountain conifers (Tunnock and others 1984; Gibson and others 1984). But when populations are transferred large geographic distances, infestations by mites increase substantially. Because mites generally deform terminal shoots, growth and development are affected greatly.

The components of adaptedness tend to be integrated by values of adjusted height. By representing growth from a common height at age 5, adjusted height was free of most genetic and environmental effects that had accrued up to that age. Consequently, the variable was capable of expressing adaptation of populations to particular environments over a short period. At low elevation, populations from mild environments had larger adjusted heights than populations from severe environments. A part of this difference was due to the high innate growth potential of populations from low elevation, and a part was due to the high susceptibility to needle cast of populations from high elevations. At PREF 1,500, populations from about 1,500 m had the largest adjusted heights; populations from extremely high elevations displayed an innately low-growth potential, while populations from low elevations suffered snow damage. At Lost Valley, however, environmental effects sufficient for adaptively differentiating populations evidently are only beginning to be expressed. Although southern populations of low growth potential displayed the smallest adjusted heights, superior performance of relatively local sources cannot yet be detected (fig. 3).

Adaptive differentiation is readily quantified from regression statistics. Table 5 shows that elevational clines are particularly steep for 7-year height, late growth, needle cast, and snow damage. Populations separated by 1,000 m are expected to differ by 16 cm (33 percent of the mean) in 7-year height largely because of a large difference in the amount of late growth. These same populations, when planted at low elevation, are expected to differ by 48 percent in leaves infected with needle cast. When planted at high elevation, they are expected to differ by 28 percent in trees damaged by the snow. Previous studies (Rehfeldt 1980) also predict that populations separated by 1,000 m will differ by 31 percent in trees damaged by a fall frost that causes a mean injury of 50 percent. Elevational clines are so steep that populations separated by merely 224 m tend to be genetically differentiated (95 percent level of probability) for late growth while those separated by 500 m are differentiated for numerous traits (table 5).

The elevational cline, moreover, is the dominant cline (table 5). For those variables in which differentiation was pronounced (height, late growth, needle cast, and snow damage), the amount of differentiation associated with 1,000 m of elevation varies from half to twice that associated with 7° latitude at a constant elevation. Consequently, differentiation per unit distance is much greater along the elevational cline than along the geographic cline.

Nevertheless, both clines arise from environmental selection along climatic gradients. Because the frost-free period decreases by 80 days across an elevational interval of 1,000 m (Baker 1944), an average difference of only 18 days in frost-free period seems sufficient for inducing differentiation of populations for late growth, a variable reflecting tolerance to early fall frosts. Consequently, the steep elevational cline reflects the rapid change in frost-free period associated with elevation. And the gentle geographic cline arises from a gradual geographic gradient in the frost-free period.

These results have direct practical application. First, quantitative estimates of differentiation along adaptive clines define the risks involved with seed transfer in artificial reforestation. Reforestation goals involve increasing productivity while maintaining adaptiveness. To accomplish this, limits of seed transfer must reflect adaptive clines. The steep elevational clines described in this study

Table 5—Quantification of the percentage differences expected between populations located along elevational and geographic clines

Variable		Difference across 1,000 m elevation	Difference across 7° latitude	Elevational interval (m) associated with *lsd* (.05)[1]
7-year height	(cm)	16	28	463
Adjusted height				
PREF 640	(cm)	14	10	544
PREF 1,500	(cm)	6	5	2,461
Lost Valley	(cm)	3	12	4,735
Late growth	(cm)	7	6	224
Needle cast	(%)	48	38	354
Mites	(%)	5	14	2,519
Shoot borer	(%)	3	10	5,129
Spring frost injury	(%)	2	2	2,268
Snow damage	(%)	28	17	643

[1]Calculated for linear regressions as the ratio [*lsd*(.05)]/*b* and for nonlinear regressions as the solution to the quadratic equation for elevations associated with $Y \pm \frac{1}{2}$[*lsd*(.05)] at the mean geographic intercept.

imply that the elevational transfer of seeds should be greatly restricted, but the gentle geographic clines imply that the lateral movement of seeds can be relatively liberal. These conclusions are corroborated by others for the same species in adjacent geographic regions (Rehfeldt 1983a, 1985a; Stoneman 1985).

Regardless, there is little doubt that adaptive variation among populations of *P. contorta* reflects physiological specialization for relatively small segments of the environmental gradient. Specialized populations develop from a balance of environmental stimuli that harmoniously adjust the developmental cycle to the physical and biotic environment. By means of this specialized evolutionary mode, coadaptive traits have been designed by natural selection to overcome ecological problems as diverse as variable frost-free periods, insect infestations, and disease epidemics. Therefore, the large geographic and broad ecological distributions of this species result from the existence of innumerable populations, each of which is specialized. Perpetuation of specialized populations is readily facilitated by cycles of even-aged reproduction whereby individuals tend to become established on sites that supported their ancestors.

As evidenced by substantial genetic variances within populations (Ying and others 1985; Rehfeldt 1985b), specialization has not led to genetic uniformity. Although migration, mutation, and the founder effect undoubtedly contribute to intrapopulation variation, much of this variation likely results from variable selection pressures associated with environmental heterogeneity in time. For long-lived stationary organisms, temporal heterogeneity not only is pronounced but also places a limit on the degree to which specialization can develop. Bryant (1976) noted that, if populations are to survive, the process of specialization cannot deplete the genetic variability required for accommodating environmental heterogeneity in time.

Forest trees of the Rocky Mountains have achieved adaptation to heterogeneous environments according to different modes. *Pseudotsuga menziesii*, like *P. contorta*, exhibits specialization, but *Larix occidentalis* Nutt. and *Pinus monticola* Dougl. are generalists: adaptive clines are relatively flat, and populations express a high fitness to a broad range of environments (Rehfeldt 1984). *Pinus ponderosa* Dougl. ex Laws., moreover, displays an intermediate mode. Thus, the specialist mode is characterizing species with broad ecological distributions while the generalist mode is characterizing species with relatively narrow distributions. Indeed, *P. contorta* and *Pseudotsuga menziesii* have greater botanical distributions and larger ecological amplitudes than any other western conifer; but the ecological distribution of *Pinus monticola* and *Larix occidentalis* is relatively small while that of *Pinus ponderosa* is intermediate (U.S. Department of Agriculture 1965). An understanding of the ecological genetics of species such as *Thuja plicata* Donn ex D. Don and *Tsuga heterophylla*, both of which have narrow ecological amplitudes and small geographic distributions, is necessary for assessing this apparent relationship between abundance and the adaptive mode.

REFERENCES

Amman, G. D.; Baker, B. H.; Stipe, L. E. Lodgepole pine losses to mountain pine beetle related to elevation. Research Note INT-171. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1973. 8 p.

Baker, R. S. Mountain climates of the western United States. Ecological Monographs. 14: 223-254; 1944.

Benson, R. E. Management consequences of alternative harvesting and residue treatment practices—lodgepole pine. General Technical Report INT-132. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 58 p.

Bryant, E. H. A comment on the role of environmental variation in maintaining polymorphisms in natural populations. Evolution. 30: 188-190; 1976.

Critchfield, W. B. Geographic variation in *Pinus contorta*. Publication 3. Cambridge, MA: Harvard University, Maria Moors Cabot Foundation; 1957. 118 p.

Critchfield, W. B. Genetics of lodgepole pine. Research Paper WO-37. Washington, DC: U.S. Department of Agriculture, Forest Service; 1980. 57 p.

Daubenmire, R.; Daubenmire, J. B. Forest vegetation of eastern Washington and northern Idaho. Technical Bulletin 60. Pullman, WA: Washington Agricultural Experiment Station; 1968. 104 p.

Draper, N. R.; Smith, H. Applied regression analyses. New York: John Wiley and Sons; 1981. 709 p.

Gibson, K. E.; James, R. L.; Livingston, R. L.; Schwandt, J. W.; Beckman, D. P.; Thier, R. W.; Marshall, J. P.; Knapp, K. A. Idaho forest and pest conditions and program summary 1983. Report 84-1. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern and Intermountain Regions; 1984. 40 p.

Hagner, M. A genecological investigation of the annual rhythm of *Pinus contorta* Dougl. and a comparison with *Pinus sylvestris* L. Studalia Forestica Suecica 81. Stockholm, Sweden: Royal College of Forestry; 1970. 26 p.

Hoff, R. J. Susceptibility of lodgepole pine to the needle cast fungus *Lophodermella concolor*. Research Note INT-349. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1985. 6 p.

Hunt, R. S. *Trisetacus* (Acarina:Eriophyoidea) on *Pinus contorta* in British Columbia: distribution, symptoms, and provenance effect. Canadian Journal of Forest Research. 11: 651-653; 1981.

Krebill, R. G. Lodgepole pine's fungus-caused diseases and decays. In: Baumgartner, D. M., ed. Management of lodgepole pine ecosystems. Pullman, WA: Washington State University Extension Service; 1975: 377-405.

Lande, R. A quantitative genetic theory of life history evolution. Ecology. 63: 607-615; 1982.

Lindgren, D.; Krutzch, P.; Twetman, J.; Kiellander, C. L. Survival and early growth of *Pinus contorta* provenances in northern Sweden. General Research Note 20. Stockholm, Sweden: Department of Forestry, Royal College of Forestry; 1976. 42 p.

Little, E. L., Jr. Atlas of United States trees. Volume 1. Conifers and important hardwoods. Miscellaneous Publication 1146. Washington, DC: U.S. Department of Agriculture; 1971. 9 p. plus 313 maps.

Lotan, J. E.; Brown, J. K.; Neuenschwander, L. F. Role of fire in lodgepole pine forests. In: Baumgartner, David M.; Krebill, Richard G.; Arnott, James T.; Weetman, Gordon F., eds. Lodgepole pine: the species and its management: symposium proceedings; 1984 May 8-10; Spokane, WA; 1984 May 14-16; Vancouver, BC. Pullman, WA: Washington State University, Office of Conferences and Institutes, Cooperative Extension; 1985: 133-152.

Pfister, R. D.; Daubenmire, R. Ecology of lodgepole pine, *Pinus contorta* Dougl. In: Baumgartner, D. M., ed. Management of lodgepole pine ecosystems. Pullman, WA: Washington State University Extension Service; 1975: 27-46.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 174 p.

Rehfeldt, G. E. Cold acclimation in populations of *Pinus contorta* from the northern Rocky Mountains. Botanical Gazette. 141: 458-463; 1980.

Rehfeldt, G. E. Adaptation of *Pinus contorta* populations to heterogeneous environments in northern Idaho. Canadian Journal of Forest Research. 13: 405-411; 1983a.

Rehfeldt, G. E. Genetic variation within Douglas-fir populations: implications for tree improvement. Silvae Genetica. 32: 9-14; 1983b.

Rehfeldt, G. E. Microevolution of conifers in the northern Rocky Mountains: a view from common gardens. In: Lanner, R. M., ed. Proceedings, eighth North American forest biology workshop; 1984 June 30-August 1; Logan, UT. Logan, UT: Utah State University, College of Natural Resources; 1984: 32-46.

Rehfeldt, G. E. Ecological genetics of *Pinus contorta* from the Wasatch and Uinta Mountains of Utah. Canadian Journal of Forest Research. 15: 524-530; 1985a.

Rehfeldt, G. E. Genetic variances and covariances in *Pinus contorta*: estimates of genetic gains from index selection. Silvae Genetica. 34: 26-33; 1985b.

Rehfeldt, G. E.; Wykoff, W. R. Periodicity of shoot elongation among populations of *Pinus contorta* from the northern Rocky Mountains. Annals of Botany. 48: 371-377; 1981.

SAS Institute. SAS user's guide. Vol. 2. Carey, NC: SAS Institute; 1982. 548 p.

Shrimpton, D. M.; Thomson, A. J. Growth characteristics of lodgepole pine associated with the start of mountain pine beetle outbreaks. Canadian Journal of Forest Research. 13: 137-144; 1983.

Steel, R. G. D.; Torrie, J. H. Principles and procedures of statistics. New York: McGraw-Hill; 1960. 481 p.

Steele, R.; Pfister, R. D.; Ryker, R. A.; Kittams, J. A. Forest habitat types of central Idaho. General Technical Report INT-144. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981. 138 p.

Stoneman, C. K. Adaptation of lodgepole pine populations of south-central Oregon; a description of genetic variation based on seedling tests. Moscow, ID: University of Idaho; 1985. 97 p. M.S. thesis.

Tackle, D. Silvics of lodgepole pine. Miscellaneous Publication 19. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1959. 24 p.

Tunnock, S.; Dooling, O. J.; Kohler, S. Montana forest pest conditions and program highlights. Report 84-2. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region; 1984. 31 p.

U.S. Department of Agriculture, Forest Service. Silvics of forest trees of the United States. Agriculture Handbook 271. Washington, DC; 1985. 762 p.

U.S. Department of Commerce. Climatic atlas of the United States. Washington, DC: U.S. Department of Commerce, Environmental Data Service; 1968. 80 p.

Vyse, A.; Navratil, S. Advances in lodgepole pine regeneration. In: Baumgartner, David M.; Krebill, Richard G.; Arnott, James T.; Weetman, Gordon F., eds. Lodgepole pine: the species and its management: symposium proceedings; 1984 May 8-10; Spokane, WA; 1984 May 14-16; Vancouver, BC. Pullman, WA: Washington State University, Office of Conferences and Institutes, Cooperative Extension; 1985: 173-186.

Wheeler, N. C.; Guries, R. P. Biogeography of lodgepole pine. Canadian Journal of Botany. 60: 1805-1814; 1982.

Ying, C. D.; Illingworth, K.; Carlson, M. Geographic variation in lodgepole pine and its implications for tree improvement in British Columbia. In: Baumgartner, David M.; Krebill, Richard G.; Arnott, James T.; Weetman, Gordon F., eds. Lodgepole pine: the species and its management: symposium proceedings; 1984 May 8-10; Spokane, WA; 1984 May 14-16; Vancouver, BC. Pullman, WA: Washington State University, Office of Conferences and Institutes, Cooperative Extension; 1985: 45-54.

Rehfeldt, G. E. Components of adaptive variation in *Pinus contorta* from the Inland Northwest. Research Paper INT-375. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1987. 11 p.

Genetic variation among 83 populations of *Pinus contorta* from the Northern Rocky Mountains of the United States was studied with 7-year-old trees planted in three contrasting environments. Analyses of nine traits reflected adaptation of populations to the biotic and abiotic environments and revealed clinal patterns of differentiation that were elevationally steep but geographically gentle. Regression models present adaptive landscapes that mirror elevational and geographic gradients in climate.

KEYWORDS: genetic variation, population differentiation, microevolution, *Pinus contorta*

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-376

February 1987

Damage to First-Year Conifers Under Three Livestock Grazing Intensities in Idaho

**James L. Kingery
Russell T. Graham
Jeffrey S. White**

CLEMSON U. LIBRARY
MAY 27 1987
PUBLICATIONS

THE AUTHORS

JAMES L. KINGERY is an assistant professor in the Department of Range Resources at the University of Idaho. He has been employed at the University of Idaho since 1977. His primary research interests emphasize range and forestry interactions. Dr. Kingery received his Ph.D. in 1985 from the College of Forestry, Wildlife and Range Sciences, University of Idaho. He received his B.S. in 1974 and M.S. in 1977 from the College of Agriculture, University of Wyoming.

RUSSELL T. GRAHAM is a research forester in the research work unit on silviculture of cedar, hemlock, grand fir, and Douglas-fir ecosystems and tree diseases of the Northern Rocky Mountains. The unit is located at the Intermountain Research Station's Forestry Sciences Laboratory, Moscow, ID. He began his career with the Forest Service in 1973 as forester on the Bitterroot National Forest and joined the Intermountain Station in 1975. He received his B.S. degree in forestry from the University of Montana and his M.S. and Ph.D. degrees in forestry from the University of Idaho.

JEFFREY S. WHITE is a range management specialist for the Soil Conservation Service, U.S. Department of Agriculture, in Willows, CA. He received his B.S. in forestry from Humboldt State University, Arcata, CA, in 1983 and an M.S. in range resources from the University of Idaho in 1985.

RESEARCH SUMMARY

During the summer and fall of 1982, a study was established on National Forests in northern and central Idaho to investigate effects of livestock grazing on seedling establishment and growth. Study areas were selected in Douglas-fir/ninebark (study area 1), grand fir/clintonia (study area 2), and western redcedar/clintonia (study area 3) habitat types that represent a high potential for both forage and timber production.

Within each of the three study areas, three uniform sites were located to represent different livestock grazing intensities (light, medium, and heavy). Field observation and records on history of grazing use were used for individual site selection. Within each grazing intensity, a 0.4-ha plot was located for observation. Actual forage utilization at each of the study sites was determined at the end of the first grazing season.

All study plots were planted at a rate of 1,977 trees per hectare. Two species were planted alternately in each study area. Study areas 1 and 2 were planted in the spring of 1983; ponderosa pine and Douglas-fir were planted in area 1 and ponderosa pine and western white pine in area 2. Study area 3 was planted in the spring of 1984 to ponderosa pine and western white pine.

Frequent, periodic observations made it possible to define and quantify causes of damage and mortality to tree seedlings. Each tree was observed seven times—six times at 3-week intervals during the first growing season and one time the following spring. By determining seasonal distribution patterns of deer and elk, and timing observations around livestock turn-on and turn-off dates, accuracy in assessing the causes of damage was ensured. A damage assessment key was developed and used to record specific types of tree damage on each study area.

The intensity of livestock utilization and livestock management practices appeared to influence damage associated with livestock, wildlife, rodents, and nonanimal factors. Direct damage from livestock varied from no trees damaged on a site receiving 27 percent utilization to 5.8 percent damage on a site receiving 81 percent utilization.

Grazing intensity also influenced damage from both pocket gophers and other rodents that forage aboveground. Where cover was reduced by grazing, there appeared to be an overall decrease in the amount of aboveground damage associated with rodents. On a site receiving 36 percent utilization, rodent damage to ponderosa pine and western white pine was 51 percent and 61 percent, respectively; however, rodent damage to ponderosa pine and western white pine on the site that received 81 percent utilization was significantly less (28 percent and 26 percent, respectively).

Damage associated with deer and elk did not appear to be related to livestock grazing intensities. Where steep terrain limited livestock utilization, however, trampling damage from big-game animals was higher than the other two study areas due to the "stair steps" provided by the scalped planting sites.

The results of this study show that grazing intensity may influence the impact that animals have on first-year establishment of tree seedlings in a plantation setting. The results also indicate that through proper livestock management direct damage from livestock can be minimal. In addition, it appears that livestock grazing may decrease damage from rodents.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Damage to First-Year Conifers Under Three Livestock Grazing Intensities in Idaho

James L. Kingery
Russell T. Graham
Jeffrey S. White

INTRODUCTION

Grazing of forestland is a traditional resource use in the Northern Rocky Mountains and much of the Western United States (Tisdale 1961). These lands have potential to produce large amounts of forage in response to moderate to high precipitation (McLean 1974). As a multiple-use aspect of these lands, forage production and grazing are important and valid uses of many of these areas (Mitchell 1982). Although grazing may be of equal or greater economic importance than timber production on drier sites (Clary and others 1975), it usually has lower value than timber production on mesic and wet sites that are common in northern and central Idaho (USDA FS 1984; Eissenstat and others 1982).

A major concern of forest resource managers is the compatibility of livestock grazing with intensive forest management. The premise that grazing may damage both natural and artificial tree regeneration, as well as cause soil compaction that may interfere with tree development, is a common concern of those responsible for regenerating cutover areas (Edgerton 1971). The general consensus is that on sites more favorable for regeneration closely controlled livestock grazing may be compatible with tree establishment (Adams 1975). But on sites where regeneration is sparse or difficult to obtain, grazing is incompatible until there is an adequate stocking of trees large enough to withstand grazing (USDA FS 1982).

Although research studies are constantly adding to our knowledge of forest and range management, few studies truly integrate these values (Kingery 1983). Consequently much of the research that has been done simply reinforces the conviction that livestock use is either compatible or incompatible with intensive forest management.

A number of studies specifically address grazing impact on tree seedlings. There is a great deal of variability in research methods and study results (USDA FS 1982). Wellner (1969) stated that "the question of grazing and tree regeneration is quite inconsistent and controversial; one can get almost any answer he wishes from the literature."

To provide more definitive information on the grazing-reforestation issue, an investigation was established to determine the effects of livestock grazing on the factors that influence the establishment and growth of seedlings. The study was located on cutover lands on the Nez Perce, Clearwater, and Idaho Panhandle National Forests. The study considered: concentration of animals; duration and timing of grazing; terrain, soil, and ground vegetation; and tree species and size. This report covers findings of the first year of study, generally considered to be the most crucial period of seedling survival.

METHODS

Study Areas

Areas were selected that have a high potential for both forage production and growth of commercial timber. Study areas were located in central and northern Idaho in three different habitat types (Cooper and others 1985) to represent a wide range of conditions. The first study area was located in a *Pseudotsuga menziesii/Physocarpus malvaceus* habitat type, which reflected fairly dry and warm conditions; the second study area was located in an *Abies grandis/Clintonia uniflora* habitat type, a mesic or intermediate set of conditions; study area 3 was located in a *Thuja plicata/Clintonia uniflora* habitat type, characterized by cool, moist conditions.

Within each of these study areas, three uniform sites were located to represent different livestock grazing intensities (light, medium, and heavy). Within each grazing intensity, a 0.4-ha plot was located. Field observation and records on the history of grazing use were used to select sites within each habitat type. Actual forage utilization at each of the study sites was determined at the end of the first grazing season.

Study Area 1: Indian Springs—The Indian Springs study area is in the Squaw Creek drainage of the Slate Creek Ranger District, Nez Perce National Forest. The area is part of the Salmon River breaks, and the general topography is quite steep, with mass wasting evident. Slope of the study area ranges from 0 to 50 percent, with an average slope of approximately 25 percent.

Majority of the soils on the study area are Typic Argixerolls, fine loamy mixed frigid family, which are moderately to well drained. Due to the mass wasting and erosion in the area, some soils have a thin surface layer.

The climate for this vicinity is subhumid, with warm dry summers and cool wet winters. The majority of the precipitation falls during the winter, with July and August being the driest months. The estimated annual precipitation for the area is approximately 45 cm. The mean annual air temperature for the study site is 9 °C.

The Indian Springs study area is in the *Pseudotsuga menziesii/Physocarpus malvaceus* habitat type, *Calamagrostis rubescens* phase, as described by Cooper and others (1985). An overstory of Douglas-fir (*Pseudotsuga menziesii*

[Mirb.] Franco) and ponderosa pine (*Pinus ponderosa* Laws.) dominate the overstory community; the *Physocarpus* union characterizes the understory. High percentages of ninebark (*Physocarpus malvaceus* Greene) and ocean-spray (*Holodiscus discolor* Pursh [Maxim.]) typify this union. Other shrub species occurring in lower percentages are serviceberry (*Amelanchier alnifolia* Nutt.), syringa (*Philadelphus lewisii* Pursh), baldhip rose (*Rosa gymnocarpa* Nutt.), spirea (*Spiraea betulifolia* Pall.), and common snowberry (*Symphoricarpus albus* [L.] Blake). Herbaceous species include largeleaf sandwort (*Arenaria macrophylla* Hook.), heartleaf arnica (*Arnica cordifolia* Hook.), wild strawberry (*Fragaria* spp.), and Columbia brome (*Bromus vulgaris* Hook.).

Current shrub vegetation on the area consists predominantly of ninebark, serviceberry, blueberry (*Vaccinium globulare* Rydb.) and currant (*Ribes* spp.). Herbaceous species include brodiea (*Brodiaea elegans* Hoover), houndstongue (*Cynoglossum* spp.), buckbean (*Thermopsis montana* Nutt.), pinegrass (*Calamagrostis rubescens* Buckl.), and orchardgrass (*Dactylis glomerata* L.).

Study Area 2: Tee Meadows—The Tee Meadows study area is located in the Vassar Meadow complex of the Palouse Ranger District, Clearwater National Forest. The area is part of the Musselshell Basalt Lands Subsection (Arnold 1975). The general topography of the area is fairly moderate. Elevation of this study area is 883 m.

The soils in this area are of the fragipan phase of the Andeptic Paleboralfs, medial over loamy mixed family. These soils, formed in a thick (35- to 65-cm) layer of volcanic ash, are very deep, moderately well drained, and underlain by loess. But because a fragipan exists, infiltration and permeability are slow to very slow. Available water capacity is low, and effective rooting depth is only 51 to 77 cm. Erosion potential is high when vegetation cover is removed.

The climate for this study area is subhumid to humid, with a mediterranean precipitation pattern of cool, dry summers and cool, wet winters. The annual precipitation for the area is 90 cm and the mean annual temperature is 7 °C.

The Tee Meadows study area is in the *Abies grandis/Clintonia uniflora* habitat type, *Clintonia uniflora* phase. This is one of the major habitat types of northern Idaho (Cooper and others 1985). An overstory of grand fir (*Abies grandis* [Dougl.] Lindl.) and an understory of moist-site forbs such as queencup beadlily (*Clintonia uniflora* [Schult.] Kunth), starry solomonplume (*Smilacina stellata* [L.] Desf.), sweetscented bedstraw (*Galium triflorum* Michx.), goldenthread (*Coptis occidentalis* [Nutt.] T. G.), fairybells (*Disporum hookeri* [Torr.] Nicholson), and American adenocaulon (*Adenocaulon bicolor* Hook.) dominate the potential natural community. Western thimbleberry (*Rubus parviflorus* Nutt.), baldhip rose, Utah honeysuckle (*Lonicera utahensis* Wats.), and blueberry are shrubs that are commonly found in seral plant communities of this habitat type.

The dominant species for the Tee Meadows study area were orchardgrass, timothy (*Phleum pratense* L.), elk sedge (*Carex geyeri* Boott), wild strawberry, sweetscented bedstraw, starry solomonplume, and buckbean.

Study Area 3: Hume Creek—The Hume Creek study area is located in the Hume Creek drainage of the St. Maries Ranger District, Idaho Panhandle National Forests. It is in the Central Idaho Rocky Mountains Major Land Resource Area (Austin 1972). Topography in this area is level to moderately sloped, with an average slope angle of 15 percent.

Soils in the Hume Creek study area were formed in thick loess layers over basalt terraces. These soils fall in the Reggear series (cool phase) and are classified as fine-silty, mixed Typic Fragiboralfs. The soils are primarily silt loams, grading to silty clay loams in the lower horizons, and are moderately deep with a fragipan occurring between 50 cm and 100 cm. The soils are well drained, with permeability being moderate to poor due to the fragipan. Available water capacity is low, and rooting depth is shallow. The erosion hazard on these soils increases from slight on the gentle slopes to severe on the steep slopes.

The climate in this area is characterized by a mediterranean precipitation pattern of cool, wet winters and cool, dry summers common to northern Idaho. The mean annual precipitation for the site is 69 cm. The mean annual air temperature is 8 °C.

This study area is located in a *Thuja plicata/Clintonia uniflora* habitat type, *Clintonia uniflora* phase (Cooper and others 1985). In the potential natural community western redcedar (*Thuja plicata* Donn ex D. Don) dominates the overstory, and the understory consists of the *Clintonia* union. The presence of queencup beadlily, sweetscented bedstraw, goldthread, rattlesnake plantain (*Goodyera oblongifolia* Raf.), and foamflower (*Tiarella trifoliata* L.) typifies this union. Unlike the other two sites, ponderosa pine does not occur as a seral tree species under natural conditions; however, it will grow where planted.

The predominant species present in the Hume Creek study area are western yarrow (*Achillea millefolium* L.), thistle (*Cirsium* spp.), wild strawberry, clover (*Trifolium* spp.), orchardgrass, and bluegrass (*Poa* spp.)

PLANTING PROCEDURES

During the spring of 1983 the Indian Springs study area was planted with 2-0 bareroot ponderosa pine and Douglas-fir obtained from the Forest Service nursery, Coeur d'Alene, ID. Each tree was planted in a scalped area 30 cm by 30 cm with use of a planting hoe. In addition, each tree was shaded using a 30-cm by 35-cm card on a 30-cm stake. The selected plot was planted at a rate of 1,977 trees per hectare. The two species were planted alternately, with a spacing of 6.7 m. This resulted in 28 rows consisting of 28 trees per row in each plot. Within each plot, an individual tree planter planted all of one species to insure uniformity of planting.

The Tee Meadows study area was also planted during the spring of 1983. Because Tee Meadows is cooler and wetter than Indian Springs, ponderosa pine and western white pine (*Pinus monticola* Dougl.) were planted. The same planting techniques were used at Tee Meadows as were used on the Indian Springs study site.

The Hume Creek study area was planted in the spring of 1984 to western white pine and ponderosa pine. The planting procedures were the same as on the other two study areas.

SAMPLING PROCEDURES

To avoid any edge effect of the planting, only the center of each plot was sampled. A 3-m buffer strip was defined on the outside of each plot. This resulted in 26 tree rows within each 0.4-ha plot available for sampling in the study.

To define and quantify causes of damage and mortality to tree seedlings during the first year of establishment, each tree in the study was observed seven times, six times at 3-week intervals during the first growing season and one time the following spring. Frequent, periodic observations made it possible to determine not only what caused damage but also when damage was occurring. Also, by determining seasonal distribution patterns of deer and elk, and timing observations around livestock turn-on and turn-off dates, we were able to further reduce error in observation.

A damage assessment key was developed and used to record specific types of tree damage on each site (appendix).

The following tabulation shows agent and the type of seedling damage that was observed during the first year of the study:

Nonanimal	Pocket gopher	Other rodents	Big game	Livestock
planting	browsing	browsing	browsing	browsing
drought	root removal	girdling	trampling	trampling
snow	tree removal			

Utilization by livestock was determined by use of protected and unprotected 1-m square plots. Vegetation was clipped and weighed on plots protected from grazing and compared to that obtained from grazed plots. The difference in weight was used to determine the percentage of utilization.

ANALYSIS

An analysis of variance was used to analyze the data. The influence of three different grazing intensities on the percentages of trees substantially damaged by livestock, pocket gophers, other rodents, wildlife, and unknown agents was computed for each row in the study. These percentages were transformed (square root of arc sine) and used in the analysis. At each site there were three utilization levels, with 26 tree rows per utilization level. Because conducting a true replicated study was logistically and financially prohibitive, tree rows were used in the analyses as replicates. Duncan's multiple range test was used to detect differences among the utilization means. The three tree species used in this study were analyzed separately.

RESULTS

The following results assess the impact of animal and nonanimal related factors on tree seedlings during the first 12 months of establishment. The first year of establishment is the most important in the life of a forest plantation. It is at this time that tree seedlings are most susceptible to numerous biotic and abiotic environmental factors that can cause mortality or reduced growth. These results identify the influence of livestock grazing intensity on those factors damaging first-year plantations. This is done for each of the three study areas.

Indian Springs

Grazing intensity appeared to influence the total percentage of ponderosa pine trees that were damaged in the different utilization levels at Indian Springs. The factors that most influenced tree damage and mortality were nonanimal causes, rodents other than pocket gophers, and wildlife (deer and elk). On the high-utilization site, 14.4 percent of the seedling damage was from nonanimal-related causes as compared to 4.9 percent of the seedlings damaged on the study site receiving an intermediate level of utilization (table 1). It appeared that rodents other than pocket gophers did the most damage in the low-utilization area, with no differences in percentage of damage detected between the intermediate and high levels.

The sum of these damaging agents was the largest in the low-utilization level (21.9 percent damage) and in the high-utilization level (24.4 percent damage). The fewest trees damaged were in the intermediate-utilization level.

The results for Douglas-fir were similar to those of ponderosa pine at the three different utilization levels. Wildlife caused the largest amount of damage (6.5 percent) on the low-utilization level (table 1). Nonanimal damage for Douglas-fir was higher on the heaviest grazed area (4.9 percent). Similar to ponderosa pine, the greatest damage and mortality occurred on the areas receiving light and heavy grazing intensities. Fewest trees were damaged on the intermediate-utilization level, where only 3.7 percent of the trees were damaged.

Tee Meadows

Damage and mortality to ponderosa pine were significantly different for each of the three utilization levels. Pocket gophers caused the most damage to the ponderosa pine seedlings. The greatest amount of damage occurred at the intermediate-utilization level (66.3 percent), with 51.2 percent at the light-utilization level and 28.8 percent damage at the heavy grazing intensity (table 2).

Nonanimal damage was the greatest at the low-utilization level (7.4 percent). In addition, no significant differences were found in damage to ponderosa pine among the grazing levels by livestock or wildlife.

The differences found among the three utilization levels for total damage were influenced most by pocket gophers, with the highest amount of damage occurring at the intermediate grazing intensity. Total damage was least on the high-utilization level (33.8 percent), with 72.8 percent of the trees damaged on the intermediate grazing level.

Fewer differences in damage were found with western white pine at the different grazing intensities than with ponderosa pine. The largest amount of damage to western white pine was caused by pocket gophers, with 61.2 percent damage occurring at the light grazing intensity and 63.8 percent damage at the intermediate grazing intensity.

Table 1—Percentage of trees to incur substantial damage[1] or mortality at Indian Springs site, for three forage utilization levels: low, 20 percent;[2] mid, 47 percent; high, 71 percent

Damage agent	Forage utilization level					
	Ponderosa pine			Douglas-fir		
	Low	Mid	High	Low	Mid	High
Nonanimal	5.1 a[3]	4.9 a	14.4 b	0.6 a	0.7 a	4.9 b
Gopher	1.8 a	1.7 a	2.5 a	2.1 a	1.7 a	4.7 a
Rodent	6.2 a	.3 a	.3 b	5.0 a	.3 b	2.6 a
Big game	7.8 a	1.7 b	5.0 ab	6.5 a	.3 b	1.4 b
Livestock	1.0 a	.6 a	2.2 a	1.2 a	.7 a	.8 a
Total	21.9 a	9.2 b	24.4 a	15.4 a	3.7 b	14.4 a

[1]Damage was determined from the overall vigor of the tree seedlings. Substantial damage percentages included tree seedlings in vigor classes 3 or 4, as described in the appendix.
[2]Actual utilization of range forage from field measurements.
[3]Different letters indicate significant differences among utilization levels. The analysis was conducted using the arc sine $\sqrt{\text{percent}}$ transformation.

Table 2—Percentage of trees to incur substantial damage[1] or mortality at Tee Meadows site, for three forage utilization levels: low, 36 percent;[2] mid, 58 percent; high, 81 percent

Damage agent	Forage utilization level					
	Ponderosa pine			Western white pine		
	Low	Mid	High	Low	Mid	High
Nonanimal	7.4 a[3]	2.7 b	2.7 b	2.9 a	1.3 b	1.0 b
Gopher	51.2 a	66.3 b	28.8 c	61.2 a	63.8 a	26.6 b
Big game	2.7 a	1.4 a	.3 a	1.7 a	.0 a	.0 a
Livestock	3.5 a	2.4 a	2.0 a	1.6 a	5.0 b	5.8 b
Total	64.8 a	72.8 b	33.8 c	67.4 a	70.1 a	33.4 b

[1]Damage was determined from the overall vigor of the tree seedlings. Substantial damage percentages included tree seedlings in vigor classes 3 or 4, as described in the appendix.
[2]Actual utilization of range forage from field measurements.
[3]Different letters indicate significant differences among utilization levels. The analysis was conducted using the arc sine $\sqrt{\text{percent}}$ transformation.

Livestock damage was significantly greater at the higher utilization levels, with 5.8 percent damage occurring at the high-utilization level and 5.0 percent damage occurring on the intermediate-utilization level, as compared to 1.6 percent damage at the light-utilization level.

Overall damage was greatest to western white pine on study sites receiving light and intermediate grazing intensities. Like ponderosa pine, most of the damage was caused by pocket gophers. The least amount of damage occurred on the study site that received high utilization.

Hume Creek

Grazing intensity appeared to have little influence on direct damage to ponderosa pine at Hume Creek (table 3). The greatest differences in damage observed were a result of wildlife- and nonanimal-related factors, with 12.5 percent damage for nonanimal at the low-utilization level as compared to 2 percent damage at high utilization. Wildlife caused 6.1 percent damage at high utilization, with 1.2 percent damaged at the moderate-utilization level. Significant differences were found in damages caused by livestock, with no damage at the low-utilization level and 2.7 percent damage at the high-utilization level. Also no significant differences were detected in the total number of ponderosa pine damaged at Hume Creek, with 11.3 percent to 15.1 percent damage observed among the grazing intensities.

Significant differences in damage to western white pine were observed among the three grazing intensities. Pocket gophers caused the greatest damage (7.9 percent) in the moderate-utilization level, with 0.3 percent damage observed in the low-utilization level. Wildlife caused 6.1 percent damage in the high-utilization level and 1.4 percent damage in the low-utilization level. Livestock damaged 3.8 percent of the western white pine seedlings and 0.3 percent of the trees in the low level of utilization. Overall the most damage to western white pine occurred under high and intermediate levels of utilization, with 19.2 percent total damage at high grazing intensity as compared to 7.5 percent damage at low utilization.

Table 3—Percentage of trees to incur damage[1] or mortality at Hume Creek site, for three forage utilization levels: low, 22 percent;[2] mid, 41 percent; high, 68 percent

Damage agent	Forage utilization level					
	Ponderosa pine			Western white pine		
	Low	Mid	High	Low	Mid	High
Nonanimal	12.5 a[3]	5.4 b	2.0 b	5.5 a	3.2 a	2.5 a
Gopher	.6 a	2.5 ab	3.4 b	.3 a	7.9 b	6.8 b
Big game	2.0 a	1.2 a	6.1 b	1.4 ab	3.3 a	6.1 b
Livestock	.0 a	2.2 b	2.7 b	.3 a	.6 a	3.8 b
Total	15.1 a	11.3 a	14.2 a	7.5 a	15.0 b	19.2 b

[1]Damage was determined from the overall vigor of the tree seedlings. Substantial damage percentages included tree seedlings in vigor classes 3 or 4, as described in the appendix.
[2]Actual utilization of range forage from field measurements.
[3]Different letters indicate significant differences among utilization levels. The analysis was conducted using the arc sine $\sqrt{\text{percent}}$ transformation.

DISCUSSION AND CONCLUSIONS

All sites considered together, direct damage from livestock was minimal. This was most apparent on the Indian Springs study site where rotational grazing management is practiced. There, direct grazing damage to both Douglas-fir and ponderosa pine was negligible. In addition, when rotational grazing is practiced, damage to tree seedlings was not found to be significantly different among utilization levels. In contrast, at Tee Meadows and Hume Creek, where rotational grazing is not practiced on the high-utilization sites, overall damage was greater. Higher grazing intensities appear to increase the potential for significant damage, and the accumulative effect of continuous and heavy grazing could be substantial in later years.

The amount of seedling damage from big-game animals was similar to that from livestock where terrain did not limit livestock movement. On the Hume Creek and Tee Meadow sites, livestock and big-game damage patterns were similar. On these sites, terrain did not limit either livestock or big-game movement. Meanwhile at Indian Springs, the greatest damage from big-game animals occurred on the light-utilization level, where elk and deer used scalped planting sites as "stair steps" on terrain too steep for livestock use. Terrain or steepness of slope could possibly be used as a controlling factor in minimizing livestock damage. Cutting units could possibly be designed to take advantage of slope conformation to control livestock damage.

Nonanimal damage also appeared to be related to grazing intensity on the Indian Springs site, with the greatest damage to tree seedlings occurring on the high-utilization site. This could be the result of past grazing history; however, it was observed that the soils on areas of steep topography were more developed than on areas of gentle-to-moderate terrain. This phenomenon, which resulted in poorer planting conditions for tree seedlings, may be a result of the mass wasting that has occurred on areas of steep topography, which routed talus material around large rock outcrops. While the remnants of these rock outcrops still exist and provide attractive areas for grazing animals, they are also sites that have had less opportunity for soil development. Because of these conditions, the potential for injury or mortality to tree seedlings from nonanimal and animal sources is higher than on the steeper, more favorable sites.

Pocket gophers were the greatest cause of tree damage in the study. It appeared that the greatest damage occurred on sites receiving the least grazing, where over half of the damage occurred aboveground during the growing season. The most favorable habitat for pocket gophers existed on the sites receiving moderate or light levels of utilization. The forbs and grasses provided adequate cover for ease of animal movement, as well as ample food for gopher population buildups. The scalps used for planting on the low-utilization sites provided areas for pocket gophers to begin and end tunnels. Thus pocket gopher damage both above and below ground was more extensive on the sites to receive intermediate to low levels of utilization.

On sites receiving moderate to heavy grazing intensities, pocket gopher damage was confined to the underground portion of the tree seedlings. There appears to be a relationship between the amount of ground cover and the amount of aboveground rodent damage. Sites receiving moderate-to-high grazing intensities appeared to be less conducive for pocket gopher movement, thus incurring less aboveground damage.

At the end of 1 year, results from this study indicate that the intensity of livestock use can influence tree seedling establishment and mortality. While the effects of grazing management practices on tree seedling establishment were not tested, it was observed that there was less damage and mortality where rotation grazing was practiced. In addition, it appears that intensity of livestock grazing may influence rodent damage. If in fact there is a relationship between ground cover and rodent damage, prudent livestock grazing may provide an opportunity to further reduce rodent damage. This possibility warrants further investigation.

REFERENCES

Adams, A. N. Sheep and cattle grazing in forests. Journal of Applied Ecology. 12: 143-152; 1975.

Arnold, F. F. Descriptions of sections and subsections of that portion of the Northern Rocky Mountain physiographic province containing the Idaho Batholith: Appendix B of the Idaho Batholith source book. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region; 1975. 342 p. and map.

Austin, M. E. Major land resource regions and major land resource areas of the United States. Agriculture Handbook 296. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service; 1972. 82 p.

Clary, W. P.; Kruse, W. H.; Larson, F. R. Cattle grazing and wood production with different basal areas of ponderosa pine. Journal of Range Management. 28: 434-437; 1975.

Cooper, S. K.; Neiman, K. E.; Steele, R. Forest habitat types of northern Idaho. Missoula, MT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1985. 210 p. Review draft.

Edgerton, P. J. The effects of cattle and big game grazing on a ponderosa pine plantation. Research Note PNW-172. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1971. 8 p.

Eissenstat, D. M.; Mitchell, J. E.; Pope, W. W. Trampling damage by cattle on northern Idaho forest plantations. Journal of Range Management. 35: 715-716; 1982.

Hedrick, D. W. Grazing mixed conifer forest clearcuts in northeast Oregon. Rangeman's Journal. 2: 6-9; 1975.

Kingery, J. L. Research response to forestland grazing needs on public lands of the northern Intermountain region. In: Proceedings, forestland grazing symposium; 1983 February 23-25; Spokane, WA. Pullman, WA: Washington State University; 1983: 85-87.

McLean, A.; Clark, M. B. Grass, trees, and cattle on clearcut-logged areas. Journal of Range Management. 33: 213-217; 1974.

Mitchell, J. E.; Eissenstat, D. M.; Irby, A. J. Forest grazing—an opportunity for diplomacy. Journal of Range Management. 4: 172-174; 1982.

Tisdale, E. W. Grazing of forest lands in northern Idaho and adjacent areas. In: Proceedings, Society of American Foresters. Washington, DC: Society of American Foresters; 1961: 150-153.

U.S. Department of Agriculture, Forest Service. Range analysis handbook. Forest Service Handbook 2209.21, R-6. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region; 1984.

U.S. Department of Agriculture, Forest Service. Timber management handbook. Forest Service Manual 2400, Supplement No. 257, R-4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Region; 1982.

Wellner, C. A. [Timber Management Research memorandum.] 1969 April 21. On file at: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Moscow, ID.

APPENDIX: TREE DAMAGE CODE KEY

Source 0. No damage

Source 1. Animal damage

Type 1.	Livestock (cattle)	
2.	Deer	
3.	Elk	
4.	Pocket gopher	
5.	Porcupine	
6.	Big game (deer + elk)	
7.	Grazing/browsing animals	
8.	Small aboveground rodent	
9.	Other	

Damage 1. Trampling

Type 1.	Stem scarring	cm
2.	Growth abnormality	degree
3.	Bud or stem broken	cm lost
4.	Trauma	degree
5.	Shade card caused growth abnormality	degree
6.	Shade card caused bud/stem breakage	degree

Damage 2. Browsing

Type 1.	Terminal bud damaged or removed	cm
2.	Terminal bud and portion of main stem damaged or removed	cm
3.	Lateral bud damaged or removed	cm
4.	Lateral bud and portion of main stem damaged or removed	cm
5.	Root damaged or removed	pct
6.	Entire tree removed	—
7.	Needles removed	pct
8.	Terminal and lateral buds damaged or removed	cm

Damage 3. Bark removal

Type 1.	Girdling (>25% circumference)	pct
2.	Stripping (>25% circumference)	cm

Damage 4. Burial

Type 1.	>25% buried	
2.	Growth abnormality due to burial	

Source 2. Nonanimal damage

Type 1.	Drought/desiccation	
2.	Stock quality	
3.	Planting and handling	
4.	Sun scald	
5.	Frost	
6.	Unknown	
7.	Snow	
8.	Shade card	
9.	Water	

Damage 1. Terminal bud

Type 0.	Terminal bud damaged	cm
1.	Terminal bud dead	—

Damage 2. Lateral bud

Type 0.	Lateral bud damaged	cm
1.	Lateral bud dead	—

Damage 3. Terminal and lateral buds

Type 0.	Terminal and lateral buds damaged	cm
1.	Terminal and lateral buds dead	—

(con.)

APPENDIX: (Con.)

Damage 4. Needles	
Type 0. Needles missing	pct
1. Needles dead	pct
Damage 5. Roots	
Type 0. Entire root	—
1. J-root	—
3. Air gap	—
Damage 6. Entire aboveground portion	
Type 0.	
1. Growth abnormality	degree
Source 3. Unknown source of damage	
Damage 1. Needles missing	pct
Damage 2. Needles dead	pct
Damage 3. Terminal bud dead	—
Damage 4. Lateral bud dead	—
Source 4. Insect damage	
Type 1. Spruce budworm	
Damage 1. Terminal bud	
Type 0. Damage	degree
1. Removal	cm
Damage 2. Lateral bud	
Type 0. Damage	degree
1. Removal	cm
Damage 3. Needles	
Type 0. Defoliation	pct

Notes:

1. Vigor is based upon percent needles chlorotic, dead or missing.
   1. 0 - 25 percent
   2. 25 - 50 percent
   3. 51 - 75 percent
   4. 76 - 99 percent
   5. 100 percent (dead)
2. Centimeters of bud or stem removed determined by "reconstruction."
3. Degree is a subjective evaluation: 1 = minimum, 4 = maximum.

Kingery, James L.; Graham, Russell T.; White, Jeffrey S. Damage to first-year conifers under three livestock grazing intensities in Idaho. Research Paper INT-376. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1987. 8 p.

Animal and nonanimal damage to first-year tree seedlings was compared under different cattle grazing intensities in three habitat types in northern and central Idaho. Because of differences in cultural practices and physical conditions, the relationship between grazing intensity and total tree seedling mortality and damage varied between study areas.

KEYWORDS: forest grazing, regeneration, animal damage

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-377

Overstory Removal and Residue Treatments Affect Soil Surface, Air, and Soil Temperature: Implications for Seedling Survival

Roger D. Hungerford
Ronald E. Babbitt

THE AUTHORS

ROGER D. HUNGERFORD is a research forester at the Intermountain Research Station's Forestry Sciences Laboratory in Missoula, MT. His current research includes forest micrometeorology and forest ecology.

RONALD E. BABBITT is an electronics technician at the Intermountain Station's Forestry Sciences Laboratory in Bozeman, MT. His duties included development of instrumentation for environmental monitoring. He is currently working on systems to monitor logging operations and to measure ground water.

RESEARCH SUMMARY

Timber harvesting and residue reduction practices that alter shade, surface thermal properties, and moisture influence energy balance and heat transfer on the site, significantly influencing temperatures. Because the problems of mortality to seedlings due to high temperature and insufficient moisture are potentially widespread and expensive, it is crucial to be able to identify problem sites during the planning process.

Following alternative overstory removal and residue reduction treatments at three locations, ground surface temperature maximums increased and minimums declined significantly as the amount of overstory removal increased. Potentially lethal high temperatures (>133 °F) occurred frequently on all sites, while potentially lethal minimum temperatures (<25 °F) occurred on two sites. Potentially lethal temperatures occurred more frequently under treatments involving greater overstory removal. Similar relationships between treatment intensity and maximum and minimum temperatures were observed among alternative surface conditions resulting from residue treatments. In general, maximum and minimum temperatures of burned and litter surfaces in clearcuts were not different, but mineral soil surfaces were significantly different from the litter surfaces under a shelterwood cutting. Temperatures of a chip surface included maximums significantly cooler than that of burned and litter surfaces. Observed mortality of planted seedlings on study sites was consistent with the pattern of potentially lethal temperatures measured on the units.

Clearcutting significantly increased soil temperatures at depths to 16 inches compared to the uncut treatment. Humus temperatures in a shelterwood were intermediate between the clearcut and uncut treatments. Surface condition also significantly altered temperatures at 2 to 16 inches deep. Average temperatures under burned, litter, and chip surfaces were all different; those under burned surfaces were warmest and those under chips were coolest. In general, the pattern of treatment differences in the soil is the same as at the surface. Overstory treatment did not influence air temperature.

If high temperatures or frosts are expected on a site, varying the amount of overstory removal or providing shade by leaving more residues on the surface may reduce the potential for seedling mortality. Scarification of the surface to provide for a mineral soil seedbed will also reduce the potential for high temperatures and, thus, seedling mortality. It is important to be aware of the thermal properties of the surface materials and understand the consequences of leaving plant litter, branches, charcoal, loosened soil, and other materials on the surface. Where the potential for frost pockets exists, cutting units should be laid out so cold drainage is not blocked. Overstory canopies can be effective in reducing the occurrence of midsummer frosts.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

March 1987
Intermountain Research Station
324 25th Street
Ogden, UT 84401

Overstory Removal and Residue Treatments Affect Soil Surface, Air, and Soil Temperature: Implications for Seedling Survival

Roger D. Hungerford
Ronald E. Babbitt

INTRODUCTION

Logging results in microclimate changes that influence seedling regeneration and subsequent forest development. The most significant and immediate microclimate changes are temperature, light, and moisture. Of the many plant processes that are influenced by temperature, light, and moisture (Kramer and Kozlowski 1979; Gates 1980), seedling establishment is one of the most crucial in the early life of a forest stand.

Temperatures from 120 to 140 °F (Hare 1961) may be lethal for first-year conifer seedlings, depending on species (Baker 1929; Silen 1960) and exposure time (Baker 1929; Levitt 1980). Condition of the protoplasm, internal water relations, and tissue mass also influence mortality (Levitt 1980). Baker (1929) stated that the limit of safety was 122 °F for 2 hours. Maximum surface temperatures on south-facing and west-facing slopes in western Montana frequently exceed 138 °F and often 149 °F (Shearer 1967), with maximums reaching 174 °F (Shearer 1981). Lotan (1964) found soil surface temperatures often reached 149 to 167 °F on gentle slopes at high-elevation sites in southwestern Montana and eastern Idaho. Surface temperatures on slash-burned clearcuts in Oregon exceed lethal levels on 69 to 97 percent of the south slopes and nearly 50 percent of the north slopes (Silen 1960; Hallin 1968). The extent (spatially and temporally) of temperatures exceeding lethal levels on sites in the Northern Rockies is not known other than for point-in-time measurements.

High temperatures on exposed soil surfaces cause significant mortality of conifer seedlings (Baker 1929; Silen 1960; Cochran 1969). Shearer (1967) reported that high temperature was the major cause of mortality of first-year western larch (*Larix occidentalis* Nutt.) seedlings on south-facing and west-facing slopes in Montana. In some cases, however, seedlings of lodgepole pine (*Pinus contorta* Dougl.) have survived temperatures of 149 to 167 °F (Lotan 1964). High heat loads created by opening the forest also cause drying of the surface through increased evaporation. As the surface dries, maximum temperatures increase (van Wijk and DeVries 1966; Cochran 1969).

Low temperatures also cause significant mortality of conifer seedlings during the growing season (Cochran and Bernsten 1973; Lotan and Perry 1983). Topography, moisture conditions, and surface thermal properties contribute to the occurrence of frosts (Cochran 1969; Fowler 1974). Lethal low temperatures vary by species from 30 to 14 °F (Cochran and Bernsten 1973; Levitt 1980).

Temperature variation at the surface and in the air layer surrounding seedlings is a function of the heat flux density at the surface and the thermal properties of the seedbed material. Expected temperature variations are described by the amount of heat energy incident upon the surface and how the heat energy is distributed at the surface. The components of heat amount and distribution are described by the equation (Rose 1966; Cochran 1969):

$$G = Rn - H - LE$$

where

- G = the heat flux density at the surface
- Rn = the net radiation flux density (measure of energy available at the surface)
- H = the sensible heat flux density into the atmosphere, including heat dissipated by air currents
- LE = heat used in latent heat of vaporization and used in evaporation and transpiration

How G influences temperature variation at the surface and in the soil depends on the volumetric heat capacity (C) and thermal conductivity (K) of the surface and lower soil horizons. A factor ($\sqrt{KC}$) called the thermal contact coefficient (Cochran 1969) integrates these two factors. Temperature variations are inversely proportional to $\sqrt{KC}$. The nature of the material, moisture content, and amount of air space (thus, compaction, texture, and soil type) influence these thermal properties. Temperatures are more extreme on organic surfaces than on mineral soil (Cochran 1969; Fowler 1974). The thermal properties of the seedbed are critically important (Cochran 1969; Fowler 1974). The equation predicts that those practices providing shade (decreasing Rn), allowing for increasing air circulation (increasing H), or decreasing surface evaporation will lower the temperature variation by reducing the amount of heat at the surface or by dissipating the heat before it raises the temperature to lethal levels.

Some degree of shading is helpful in reducing seedling mortality due to high and low temperatures (Shearer 1967; Ryker and Potter 1970; Strothman 1972; Cochran 1975).

Logging residues and vegetation provide shade, which reduces temperature extremes, thus increasing survival (Edgren and Stein 1974).

This paper reports postharvest temperatures at the soil surface (surface-air interface), in the air (to 4.5 ft), and in the soil (to 16 inches) following several levels of overstory removal and for four surface conditions resulting from several residue treatments. Temperatures are compared with adjacent uncut stands and with expected responses based on heat fluxes and thermal properties of the surfaces. Consistency of treatment response is examined by looking at results from three stands in different habitat types. Measured temperatures represent the period immediately following treatment to 8 years later. The potential for seedling mortality, based on high and low temperature data, is compared with actual seedling survival data.

STUDY AREAS AND METHODS

We had two study sites in the Flathead Range of Montana and one in the Gros Ventre Mountains of Wyoming. These sites represent a range of climatic conditions that occur in the Northern Rocky Mountains. May through September precipitation ranges from 25 to 45 percent of the annual amount and varies considerably with topography. Average temperatures also vary considerably throughout the region. Ordination of these three sites along moisture and temperature gradients (fig. 1) is based on growing season May through September precipitation totals and July temperatures. Climax forest series (Pfister and others 1977) are Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.).

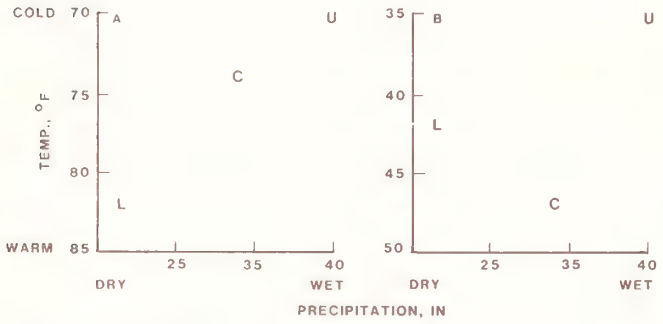


Figure 1—Ordination of study areas—Coram (C), Lubrecht (L), and Union Pass (U)—along a moisture (annual) and temperature gradient based on July average maximum temperature (A) and July average minimum temperature (B).

Treatments

Treatments on the study sites included: (1) a silvicultural prescription requiring overstory removal that varied from none through thinnings, selection cuts, and shelterwoods to clearcutting; and (2) a postharvest residue treatment varying from none to treatments of complete removal, piling, chipping, and burning. Surface conditions of litter, burned, mineral soil, and chips resulting from residue treatments were evaluated (fig. 2). This study is superimposed on a larger study. A description of specific treatments used for each study area follows.

Lubrecht Experimental Forest—This site is about 35 miles northeast of Missoula, MT, at an elevation of 4,000 ft. The terrain is gently rolling (slopes 0 to 5 percent), with west to northwest aspects. Climatic data, taken at the forest headquarters since 1956 (Montana Forest and Conservation Experiment Station 1983), indicate an average annual precipitation of 18 inches. Maximum July air temperatures average 81.6 °F, and minimum July air temperatures average 42.5 °F.

Tree cover prior to treatment was a mixed size and age class Douglas-fir forest. Western larch and ponderosa pine (*Pinus ponderosa* Laws.) were significant components of the stand. This area has a long history of selective logging where merchantable trees were periodically removed from the stands. Habitat type (Pfister and others 1977) is *Pseudotsuga menziesii/Vaccinium caespitosum* (PSME/VACA).

Logging was done in 1977 with ground skidding equipment. The following overstory treatments were compared to the uncut stand:

1. **Clearcut**. All merchantable trees were removed on a 15-acre clearcut and the rest of the material was felled, leaving 29 tons per acre of residue.
2. **Understory removal**. Treatment removed about 40 percent of the merchantable volume by cutting the smaller diameter material and leaving the better sawtimber and large pole stems as an overstory. About 18 tons per acre of residue was left on the surface. The residual overstory transmitted about 50 percent of full sunlight.
3. **Shelterwood**. About half of the merchantable volume was removed, leaving an overstory of small sawtimber and pole stems. Dense clumps of saplings and poles were selectively thinned. The residual overstory transmitted about 60 percent of full sunlight. This was a common treatment in this type of stand in 1977.
4. **Uncut**. An adjacent uncut area was used as the control.

Residue reduction treatments on the study units included the following:

1. To simulate close utilization, all residues down to 1 inch in diameter were removed. The small material was bunched by hand prior to skidding. The surface was quite uniform looking after treatment (fig. 2B). Except for skid trails, the understory vegetation was essentially undisturbed. The surface condition used for temperature measurement was a litter surface, made up of small twigs, leaf and needle litter, and duff. About 10 percent of the surface was exposed mineral soil.
2. A pile-and-burn treatment in the shelterwood overstory treatment left most of the surface (except under the piles) in the litter and mineral soil surface conditions with an appearance like the close utilization treatment. The litter and mineral soil surface conditions were used for temperature measurement.
3. Broadcast burning in the clearcut resulted in a 64 percent reduction of slash (Steele 1980) creating a completely blackened area with some mineral soil exposed

(A)

(B)

(C)

Figure 2—Postharvest residue treatments for providing different surface conditions used for temperature measurement: (A) broadcast burning provided the burned surface; (B) close utilization provided the litter surface; (C) residues chipped and spread back on the site provided the chip surface of Union Pass.

(fig. 2A). The surface condition on this treatment used for temperature measurements consisted of blackened litter, ash, and small charcoal pieces. Areas with large, partially burned residues were avoided.

Surface conditions evaluated on each of the overstory and residue reduction treatments are shown in the following tabulation:

Overstory treatments evaluated	Residue reduction treatments	Surface conditions evaluated
1. Clearcut	Broadcast burn, close utilization	Burned, litter
2. Understory removal	Close utilization	Litter
3. Shelterwood	Pile and burn	Litter mineral
4. Uncut	—	Litter

Small containerized seedlings of ponderosa pine, Douglas-fir, and western larch were planted each year following treatment (1979 to 1982). In the spring of each year, 23 seedlings were planted in each residue subtreatment within each overstory treatment. A 2- by 2-ft area was scarified around each seedling at the time of planting.

Coram Experimental Forest—This site is 5 miles south of West Glacier, MT, at an elevation of 5,000 ft. All treatments are on east-facing aspects with slopes from 40 to 60 percent. The climatic information for the area (Hungerford and Schlieter 1984) indicates an average annual precipitation of 33 inches at the treatment units. Maximum July air temperatures average 74 °F, and minimum July air temperatures average 47 °F.

Tree cover prior to treatment was a 320-year-old Douglas-fir/western larch forest. The predominant species were Douglas-fir and western larch. Subalpine fir and Engelmann spruce (*Picea engelmannii* Parry) were common, with some western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), western white pine (*Pinus monticola* Dougl.), and paper birch (*Betula papyrifera* Marsh.) present. Habitat type (Pfister and others 1977) is *Abies lasiocarpa/Clintonia uniflora* (ABLA/CLUN), *Clintonia uniflora* phase or *Xerophyllum tenax* phase. At the upper elevations the *Menziesia ferruginea* phase was evident.

Overstory treatments on this study site were:

1. **Clearcut.** Clearcuts ranged from 2 to 17 acres. Logging was completed during 1974 using a running skyline yarder. Prebunched residues were also removed with the skyline yarder. Mechanical scarification was essentially limited to the skyline corridors.

2. **Uncut**. An adjacent uncut area was used as the control.

Residue reduction treatments on the clearcut included the following:

1. Broadcast burning resulted in a 20 percent duff reduction (Artley and others 1978). High water content in the duff layer was responsible for not reaching prescription levels of 50 percent mineral soil exposed. The surface condition used for temperature measurement consisted of blackened litter, ash, and small charcoal pieces. Areas with large, partially burned residues were avoided. Burning was done in early September 1975.

2. To simulate close utilization, all residues down to 1 inch in diameter were removed. Except for skyline corridors, the understory vegetation was essentially undisturbed. The surface was a mosaic of vegetation and exposed litter surfaces. The surface condition used for temperature measurement was a litter surface made up of small twigs, leaf and needle litter, and duff. Little mineral soil was exposed. The following tabulation shows the surface conditions evaluated for each overstory and residue reduction treatment:

Overstory treatments evaluated	Residue reduction treatments	Surface conditions evaluated
1. Clearcut	Broadcast burn, close utilization	Burned, litter
2. Uncut	—	Litter

Annually for 4 years following both treatments, 25 bare root (2-0) seedlings of Douglas-fir and Engelmann spruce were spring planted. Survival and growth measurements were made periodically.

Union Pass—This site is 40 miles southwest of Dubois, WY, on the Bridger-Teton National Forest at an elevation of 9,200 ft. Slope ranges from 5 to 20 percent on an east aspect. Climatic data for this area are not available, and the nearest stations are considerably lower in elevation. Correcting for elevation and slope, annual precipitation is estimated to be 35 to 40 inches. Mean July maximum air temperature is about 70 °F, and mean July minimum air temperatures are 35 to 40 °F.

Tree cover prior to treatment was overmature lodgepole pine (160 years old) with small amounts of Engelmann spruce, subalpine fir, and limber pine (*Pinus flexilis* James). Habitat type (Steele and others 1983) is *Abies lasiocarpa/Vaccinium scoparium* (ABLA/VASC). Understory vegetation was sparse.

Overstory treatments on this study site were:

1. **Clearcut**. Clearcutting was done in 1971 using a feller buncher and ground skidding (Benson 1982).

2. **Uncut**. An adjacent uncut area was used as the control.

Residue reduction treatments within the clearcut included the following:

1. Broadcast burning, done 2 years after logging (spring 1973), resulted in 30 percent mineral soil exposed and reduction in litter depth from 1 inch to 0.71 inch (Benson 1982). The surface condition used for temperature measurement consisted of blackened litter, ash, and small charcoal pieces. Areas with large, partially burned residues were avoided.

2. To simulate close utilization, all residues down to 1 inch in diameter were removed. This treatment exposed mineral soil on 42 percent of the surface and reduced the understory vegetation cover considerably. After treatment, 19 tons per acre of woody material remained. The surface condition used for temperature measurement was a litter surface made up of small twigs, leaf and needle litter, and duff.

3. On half of the close-utilization treatment area, an amount of residue equivalent to that removed was chipped and spread back on the site (fig. 2C). The average depth of the chips was about 4 inches. No mineral soil or vegetation was exposed. The surface of the chips was used as the surface condition for temperature measurement.

Surface conditions evaluated on each of the overstory and residue reduction treatments are shown in the following tabulation:

Overstory treatments evaluated	Residue reduction treatments	Surface conditions evaluated
1. Clearcut	Broadcast burn, close utilization, chips spread	Burned, litter, chips
2. Uncut	—	Litter

Bare root (2-0) seedlings of lodgepole pine were planted in the spring the first year after treatment on all treatments. Spot seeding was also done. At the time of planting and seeding, 18-inch square areas were scarified around each spot or seedling.

Measurements

Surface, air, and soil temperature were monitored for the overstory treatment and surface conditions described for each study area. Specific temperature measurements taken for each study site and treatment combination are shown in the tabulation for each study area and in table 1. The time and duration of measurements by site are shown in table 2. The term "surface" is used to indicate the surface exposed to the atmosphere, whether the exposed material is litter, ash (from burning), mineral soil, or chips. Measured surface temperatures are actually 0.04 to 0.08 inch below the true surface. Temperature sensors were installed close to the surface by covering with one layer of the surface material—for example, one leaf, one thickness of needles, one layer of soil (enough to cover the metal), or one layer of chips. It was necessary to frequently visit the sensors and reset them if they were uncovered. Air temperature sensors at 4.5 ft above the surface at Lubrecht and Coram were placed in standard Cotton Region type shelters.

At Union Pass, air temperatures were measured at 8 inches and 4.5 ft above the surface. Sensors were placed in specially constructed shielded tubes. Soil temperatures in the humus layer at 0.4 to 1.2 inches below the surface were measured at Lubrecht and Coram. Temperatures in mineral soil at 2, 8, and 15.7 inches deep were measured at Union Pass. Sensors at Union Pass were pushed horizontally into the undisturbed soil of the wall of a hole dug to the proper depth, which was then backfilled.

Table 1—Temperature measurements taken by study site, overstory, and surface condition

Measurement location	Study site								
	Lubrecht			Coram			Union Pass		
	Surface	Air	Soil	Surface	Air	Soil	Surface	Air	Soil
Overstory treatment:									
Uncut	x	x	x	x	x	x	x	x	x
Clearcut	x	x	x	x	x	x	x	x	x
Shelterwood	x	—	x	—	—	—	—	—	—
Understory removal	x	—	—	—	—	—	—	—	—
Surface condition:									
Litter	x	—	—	x	—	—	x	x	x
Mineral soil	x	—	—	—	—	—	—	—	—
Burned	x	—	—	x	—	—	x	x	x
Chips	—	—	—	—	—	—	x	x	x

Table 2—Length of time following treatment that temperatures were measured by study site

Study site	Years following treatment						
	1	2	3	4	5	6	7
Lubrecht	x	x	x				
Coram	x	x	x	x	x	x	x
Union Pass[1]						x	

[1]Temperatures were measured for only 1 year.

Temperatures were measured using small, 0.064-inch diameter, thermistor beads inserted in 0.094-inch diameter by 0.5-inch long stainless steel tubing. Shielded 30-gauge wire attached to the thermistor ran 6 to 10 ft to a junction box. Multiconductor cables (18-gauge) up to 2,500 ft long were connected from the junction box to a recording data acquisition system. Each data acquisition system handled from 16 to 40 temperature sensors. Temperatures were recorded hourly on a 12-month basis for varying lengths of time (table 2).

Net radiation was measured on all sites for some of the treatments. Continuous monitoring of net radiation was done for the clearcut and uncut treatments at Coram for 4 years and at Lubrecht for 3 years. Net radiation measurements were also made over each of the surface treatments at noon on a clear day at Lubrecht and Union Pass. These data are used in the discussion to help explain how treatments affect temperature.

Analysis

Analysis of research results involved: (1) evaluating effects of overstory removal treatment on surface, air, and soil temperatures; and (2) evaluating effects of surface condition, resulting from residue treatments on surface, air, and soil temperatures. The discussion of results is presented in that order. Because treatment effects are influenced by the elevation, terrain, and climatic characteristics of the specific locations studied, results are also generally presented separately for the three study sites. As discussed earlier, the range of overstory treatments and surface conditions, as well as temperature observations, also varies by site. Consequently, between-site comparisons are necessarily limited.

To evaluate treatment effect on surface temperature, we used two types of summaries: (1) monthly average maximum and minimum temperatures were calculated, and (2) the occurrence of potentially lethal temperatures—referred to as hot events and cold events—was tabulated. Statistical tests (to be described later) determined treatment differences for maximum and minimum temperature by month for May through October. The percentage of months, over the measurement period, that differences were significant was then compared for the overstory treatments and surface conditions.

We calculated the number of hot events and cold events based on surface temperatures, then used these to indicate the hazard for seedling mortality. A hot event (HE) is defined as 2 or more consecutive hours of temperatures that are greater than 122 °F or 1 hour at 133 °F or higher. A cold event (CE) is an occurrence of minimum temperature of 23 °F or colder. These thresholds—122, 133, and 23 °F—were picked to represent average lethal levels for several tree species (Baker 1929; Hare 1961; Levitt 1980). The HE's and CE's are summed over the growing season, then used to calculate the percentage of days that they occurred within the period. Neither the HE nor the CE is intended to suggest that seedling mortality will invariably result from these events, but they do represent a significant hazard to survival. We then compared HE and CE data with measured seedling survival on the study areas.

To evaluate treatment effect on air temperatures, we used daily maximum and minimum values and average day and night temperatures. We used the day and night average temperatures because they influenced growth of tree seedlings (Cleary and Waring 1969; Hellmers and others 1970).

Because soil temperatures are much more stable than surface or air temperatures, daily averages were used to compare treatments at depths below 2 inches. Temperatures in the humus layer (0.4 to 2.0 inches deep) are included in the results as soil temperatures. Analysis of the humus layer includes maximum and minimum temperatures and HE's and CE's. Temperatures in the root zone

are discussed relative to their effects on seedling growth and root development.

Tests for significant treatment effects on surface temperature were made using one-way analysis of variance to determine if treatments were different for maximum and minimum temperatures (by month). Also, tests of treatment differences in air and soil temperatures were evaluated using one-way analysis of variance. Analyses were run only for data from May through October. Duncan's multiple range test was used to test for individual treatment differences. If variances were not homogeneous, we used approximate *t*-tests. All tests were done at the 0.05 significance level. Differences in the overstory removal treatments were compared using temperatures measured on the litter surface condition of each treatment. Differences between the surface conditions were compared using a common overstory removal treatment (usually the clearcut). Mineral soil and litter surface conditions at Lubrecht, however, were compared in the shelterwood treatment.

OVERSTORY REMOVAL AND TEMPERATURE

Surface, air, and soil temperature data accumulated from treated units were analyzed first to evaluate the effects of level of overstory removal on temperature. To compare overstory treatments on a common basis, data from the litter surface condition were used.

Surface Temperature

Lubrecht—The amount of overstory removal significantly influenced maximum surface temperatures, mean monthly maximum surface temperatures being significantly warmer where all or most of the canopy was removed (table 3). From May through October of the first 3 years after harvesting, temperatures on the clearcut surface were significantly warmer than those on the shelterwood surface 40 percent of the months, were equal for 40 percent of the months, and were significantly lower for the other months. Over the 3 years, surface temperatures on the clearcut and shelterwood treatments were significantly warmer for 80 percent of the months than were surface temperatures on the understory removal or uncut treatments. Surface temperatures on the understory removal for some months were up to 11 °F warmer than on the uncut, but for 60 percent of the months differences were not significant.

Maximum surface temperatures were observed as high as 165 °F and often exceeded 133 °F (fig. 3) for the clearcut and shelterwood treatments. Temperatures of 122 °F

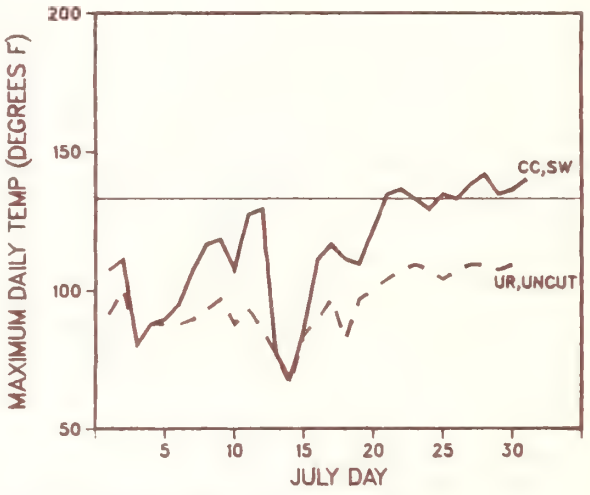


Figure 3—Maximum daily ground surface temperatures in July 1980 at Lubrecht for the clearcut (cc), shelterwood (sw), understory removal (ur), and uncut treatments. Surface condition is litter. The horizontal line through the graph is 133 °F, a seedling survival threshold.

Table 3—Average maximum surface temperatures (°F) by month for 1978, 1979, and 1980 for the overstory treatments at the Lubrecht study site. Data from the litter surface were used for all treatments. Values for a month (months are not compared) having different letters are significantly different at the 0.05 level.

Overstory treatment	May	June	July	Aug.	Sept.	Oct.
			1978			
Uncut	61a	90a	102a	95a	75a	75b
Understory removal	72b	100b	106a	86a	77a	61a
Shelterwood	72b	106b	126b	117b	93b	79b
Clearcut	93c	126c	138c	118b	97b	93c
			1979			
Uncut	66a	75a	—	—	93a	68a
Understory removal	77b	86a	—	—	91a	70a
Shelterwood	82b	100b	—	—	126c	84b
Clearcut	104c	126c	—	—	113b	81b
			1980			
Uncut	—	86a	104a	99a	70a	61a
Understory removal	—	88a	95a	102a	81b	64a
Shelterwood	—	93ab	115b	127c	100c	79b
Clearcut	—	97b	115b	118b	82b	70ab

Table 4—Average minimum surface temperatures (°F) by month for 1978, 1979, and 1980 for the overstory removal treatments at the Lubrecht study site. Data from the litter surface were used for all treatments. Values for a month (months are not compared) having different letters are significantly different at the 0.05 level.

Overstory treatment	May	June	July	Aug.	Sept.	Oct.
			1978			
Uncut	34b	39b	43b	41b	37b	27b
Understory removal	35b	38b	41b	39b	36b	24b
Shelterwood	36b	40b	44b	41b	38b	26b
Clearcut	26a	30a	35a	34a	28a	12a
			1979			
Uncut	34b	37b	—	—	37c	36c
Understory removal	34b	36b	—	—	33b	26b
Shelterwood	34b	36b	—	—	36bc	28bc
Clearcut	25a	29a	—	—	25a	17a
			1980			
Uncut	—	44b	45c	40c	38b	30b
Understory removal	—	47b	45cd	38b	39b	28b
Shelterwood	—	47b	47d	40bc	39b	31b
Clearcut	—	40a	38b	32a	33a	23a

or greater were measured from April (12 days after snowmelt) into October. Maximums on the understory and uncut treatments rarely exceeded 122 °F. Figure 3 is representative of the patterns observed for most summer months over the 3 years.

The degree of overstory removal also significantly affected minimum surface temperature (table 4). Removal of up to about 50 percent of the overstory (understory removal and shelterwood) did not cause minimum temperatures to fall lower than in the uncut stand. However, removal of all the overstory caused minimum temperatures to be significantly lower than on the shelterwood, understory removal, or uncut treatments for all months.

Minimum temperatures on the clearcut in 1978 were as low as 18 °F in June, 25 °F in July, and 21 °F in August. By September nearly every night was below 32 °F, with a low of 10 °F. Temperatures below 32 °F were not observed on the shelterwood or uncut treatments, and only occasionally on the understory removal treatment in June, July, or August (fig. 4).

The same pattern seemed to exist in 1979, but instrument failure precluded records in July and August. The summer of 1980 was warmer; no temperature below 32 °F was recorded in July.

Hot event days, when the temperature exceeded the lethal threshold, occurred on the clearcut and shelterwood treatments from May through October on 14 to 37 percent of the days (table 5). The probability of an HE was greater on the clearcut, but the difference is not significant. No HE's occurred on the understory removal treatment, and only three were measured on the uncut control over the 3 years. These results suggest that the potential for seedling mortality due to high temperatures is quite high on the clearcut and shelterwood treatments, but almost nonexistent in the uncut stand and on the understory removal treatments.

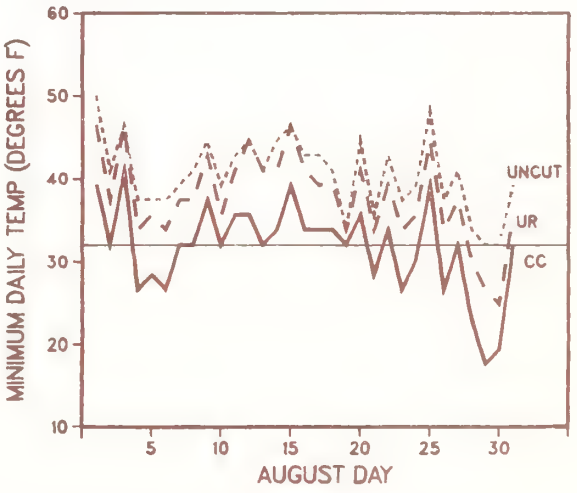


Figure 4—Minimum daily ground surface temperatures in August 1980 at Lubrecht for the uncut, understory removal (ur), and clearcut (cc) treatments. Temperatures in the shelterwood (sw) were the same as the understory removal. The surface condition was litter.

On the surface of the clearcut, cold event days—when the temperature dropped to the lethal threshold of 23 °F or below—occurred on 16 to 26 percent of the days in May through September the first 2 years after treatment. During the third year none occurred on the clearcut. During the 3 years following treatment, only one CE occurred on the uncut and understory removal treatments and none on the shelterwood treatment. Most of the CE's occurred in May and September (75 to 80 percent), but a significant number occurred in June, July, and August. Like the HE's, the results show that a potential for seedling mortality due to low temperatures exists on the clearcut treatment.

Table 5—Hot events (percentage of possible days) for the overstory treatments at several study sites. Data represent the May through October period for 1 to 7 years after treatment. Data for the litter surfaces on the clearcut were used when they were available. If not, data from the burned surface were used.

Study site	Overstory treatment	Years after treatment						
		1	2	3	4	5	6	7
		Percentage of possible days						
Lubrecht	Uncut	1	0	2	—	—	—	—
	Understory removal	0	0	0	—	—	—	—
	Shelterwood	14	16	25	—	—	—	—
	Clearcut	28	37	23	—	—	—	—
Coram	Uncut	2	0	0	—	—	—	—
	Clearcut	36	27	23	29	29	6	1
Union Pass	Uncut						0	
	Clearcut						65	

In summary, the clearcut treatment on the Lubrecht site creates conditions with a high potential for seedling mortality due to high and low temperatures. The shelterwood treatment had a high potential due to high temperatures but not to low temperatures. The residual stand canopy in the shelterwood is open enough to let incident radiation warm the surface, yet it is dense enough to hold heat in at night, slowing radiational cooling. Maximum and minimum temperatures in the understory and uncut treatments typically are not high enough or low enough for potential seedling mortality. Figure 5 shows the maximum and minimum temperature relationships for each treatment on a typical summer day.

Other Sites—Only data for the clearcut and uncut treatments are available on the other two sites. Data from the Coram and Union Pass study sites also demonstrate that clearcutting results in significantly warmer and colder surface temperatures. Data on HE's at Coram and Union Pass (table 5) are comparable to the results observed at Lubrecht. The potential for seedling mortality (due to high temperatures) is quite high on the clearcut and low in the uncut stand. The frequency of HE's is high (65 percent) at Union Pass; only data for the month of July are available. Logging significantly increased the potential for seedling mortality at Coram and Union Pass.

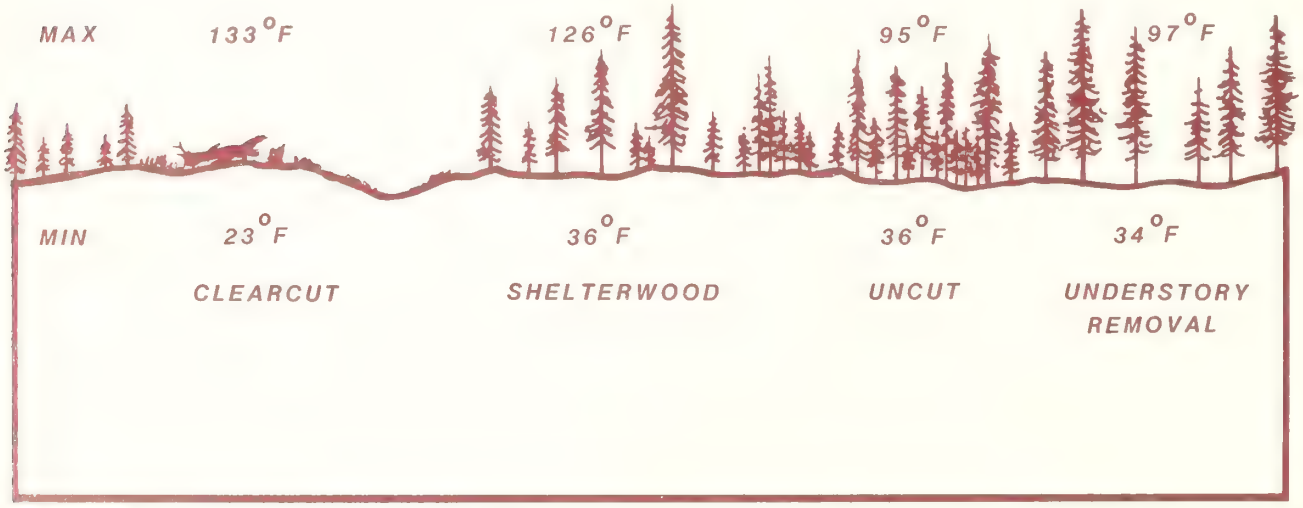


Figure 5—Daily maximum and minimum surface temperatures (°F) by overstory treatment at Lubrecht, August 29, 1978.

Minimum surface temperatures at Coram and Union Pass were significantly colder on the clearcut treatment. Results for these two sites between the clearcut and uncut follow the same pattern as at Lubrecht. Average minimum temperatures are warmer for Coram than for Lubrecht. This appears to be a result of topographic differences.

At Coram the CE's following clearcutting were not as frequent as at Union Pass. The frequency of CE's was low at Coram, and they occurred only in May or September—none in June, July, or August. The frequency of CE's varied from 0 to 45 percent of the nights in July at Union Pass. The effect of surface condition is discussed later.

Comparison With Expected Results—The results reported here are consistent with and explained well by the energy balance equation. The major effect of the overstory removal treatments was to increase energy incident upon the surface (Rn) (fig. 6). Increased Rn causes an increase in the heat flux density at the surface (G). Changes in convective heat loss (H) and latent heat loss by evaporation and transpiration (LE) are not able to dissipate the added heat, which results in increased temperature variation at the surface. Although the temperature differences were not significant for all treatments for all months, the trend of increasing growing season surface temperatures with increasing levels of canopy removal was observed (table 3 and fig. 3). The effects of vegetation influence on shade will be discussed under the surface condition section.

Because the surface condition of all treatments for the overstory removal comparisons is the same (litter), the thermal properties did not significantly influence the temperature differences. Higher surface temperatures on the clearcut and shelterwood treatments not only increase the potential for seedling mortality due to high temperatures, but also are effective in drying the surface layers, which creates additional moisture stress. The drier surface conditions in turn lower volumetric heat capacity and thermal conductivity, which further increases temperature variation.

Minimum surface temperatures for the treatments are also explained well by the same factors (table 4 and fig. 4). The more exposed surfaces, where more of the canopy has been removed, are subject to greater radiational cooling and thus lower temperatures. On the shelterwood treatment that admits about 60 percent of full sun, the canopy is sufficient enough to limit radiational cooling, which explains the absence of CE's, and to reduce the potential mortality due to low temperatures. In addition to the effect of the Rn term, topographic conditions at Lubrecht and Union Pass are such that cold air can accumulate, creating frost pockets. In these cases the H term is affected. More will be said about this in the discussion of the surface conditions.

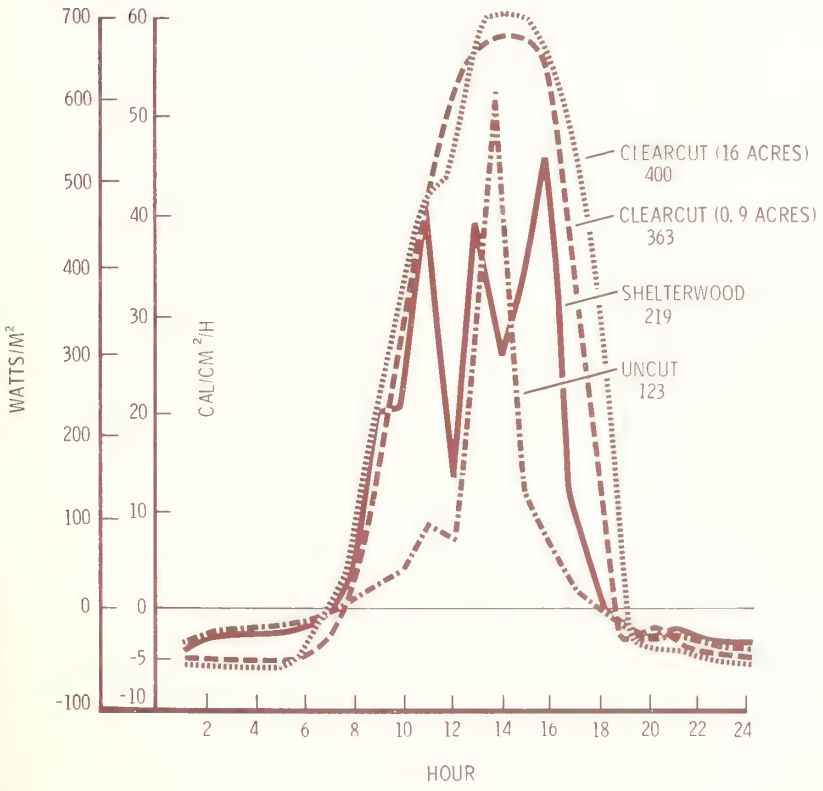


Figure 6—Diurnal variation in net radiation by cutting method on June 18, 1976, Coram Experimental Forest. Daily totals are given for each treatment in cal cm^{-2}.

Air Temperature

Air temperatures at 4.5 ft above the surface in clearcut units were not significantly warmer than above the surface in uncut units at any of the sites. Comparison using accumulative degree days over the May through October season did not reveal significant differences either. Data from Coram and Union Pass show that topographic position influences air temperature much more than clearcutting. Monthly average minimum temperatures in openings at the toe of a slope were 5 to 12 °F cooler than openings a few hundred feet up the slope (fig. 7). Monthly average maximum temperatures were at least as warm at the toe of the slope as in openings on the slope.

Soil Temperature

Lubrecht—Daylight average and maximum temperatures in the humus (O_2) layer 0.4 to 1.2 inches deep at Lubrecht over the 3 years were significantly warmer on the clearcut than in either the shelterwood or uncut treatments (fig. 8). Humus in the shelterwood was significantly warmer than in the uncut. Maximum humus temperatures were as high as 136 °F on the clearcut, and July average maximum was about 115 °F. The HE's occurred, but were not frequent (10 during the 3 years). Maximums on the shelterwood were nearly as high at 131 °F, with a July average maximum of 111 °F in 1978. Temperatures were much colder in 1979 and 1980, with a July average of about 86 °F. Only three HE's occurred in the shelterwood, all in 1978. The maximum humus temperatures on the uncut site were 91 °F.

Minimum and night average humus temperatures were significantly colder on the clearcut than in the shelterwood or uncut treatments. Minimum humus temperatures observed (May through September) were 18 °F in the clearcut and 21 °F in the shelterwood. Average July minimums were 43 °F in the clearcut and 50 °F in the shelterwood and uncut treatments.

Other Sites—Humus or upper level soil temperatures at Coram and Union Pass were measured at depths from 1.2 to 2.0 inches. Absolute maximum temperatures ranged from 73 to 90 °F in the clearcut and were significantly warmer than in the uncut treatments. Night minimums at Coram in the clearcut were not significantly colder than in the uncut. The clearcut at Union Pass was significantly warmer at night than the uncut for the short measurement period. We do not know the reason for this reversal, yet the 24-hour cumulative number of degree hours—those greater than 32 °F—is 80 percent higher in the clearcut than in the uncut.

Soil temperatures at depths from 2 to 16 inches were only measured on clearcut and uncut treatments at Union Pass. Temperatures at these depths were significantly warmer in the clearcut than in the uncut. Temperatures at 2 inches deep averaged nearly 12 °F warmer in the clearcut broadcast burn than in the uncut, 11 °F at the 8-inch depth, and almost 10 °F more at the 16-inch depth (fig. 9).

Summary

Temperatures increased from the ground surface to depths of 16 inches as a result of clearcutting. Site location has little or no effect on the treatment differences, though the maximums and average temperatures are higher at some locations. The magnitude of differences decreases with increasing depth, yet the differences remain statistically significant.

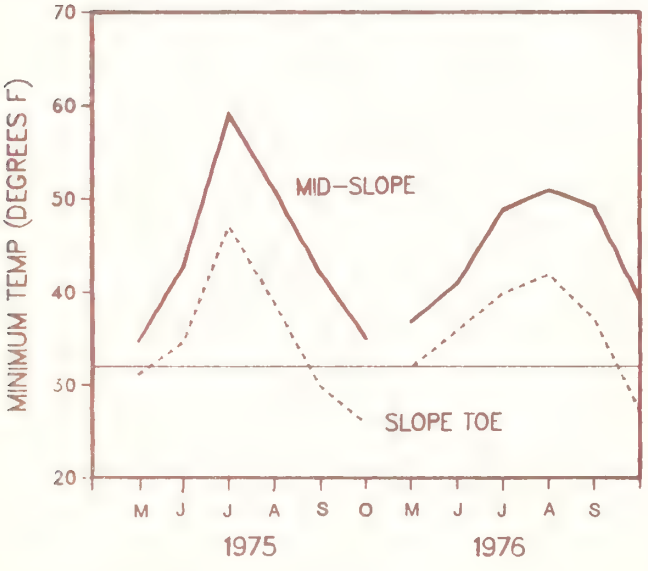


Figure 7—Mean monthly minimum air temperatures at the toe of a slope and at midslope on the Coram Experimental Forest. Temperatures are for May through October of 1975 and 1976.

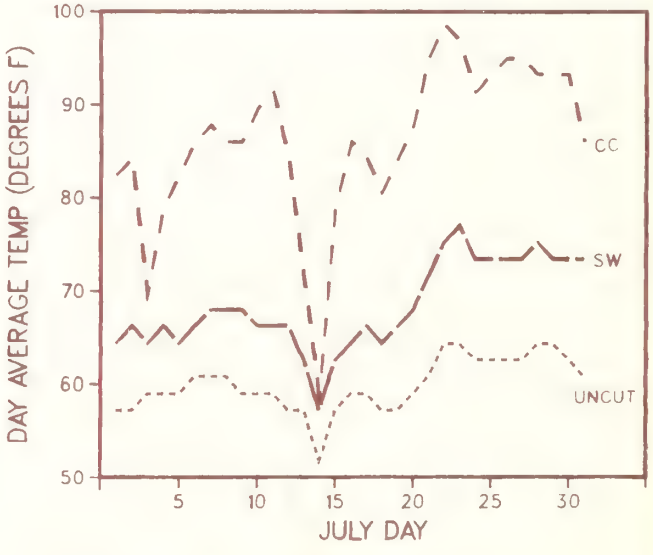


Figure 8—Daylight average temperatures of the humus (O_2) layer (0.4 to 1.2 inches depth) on the clearcut (cc), shelterwood (sw), and uncut treatments at Lubrecht in July 1980. Surface condition was litter.

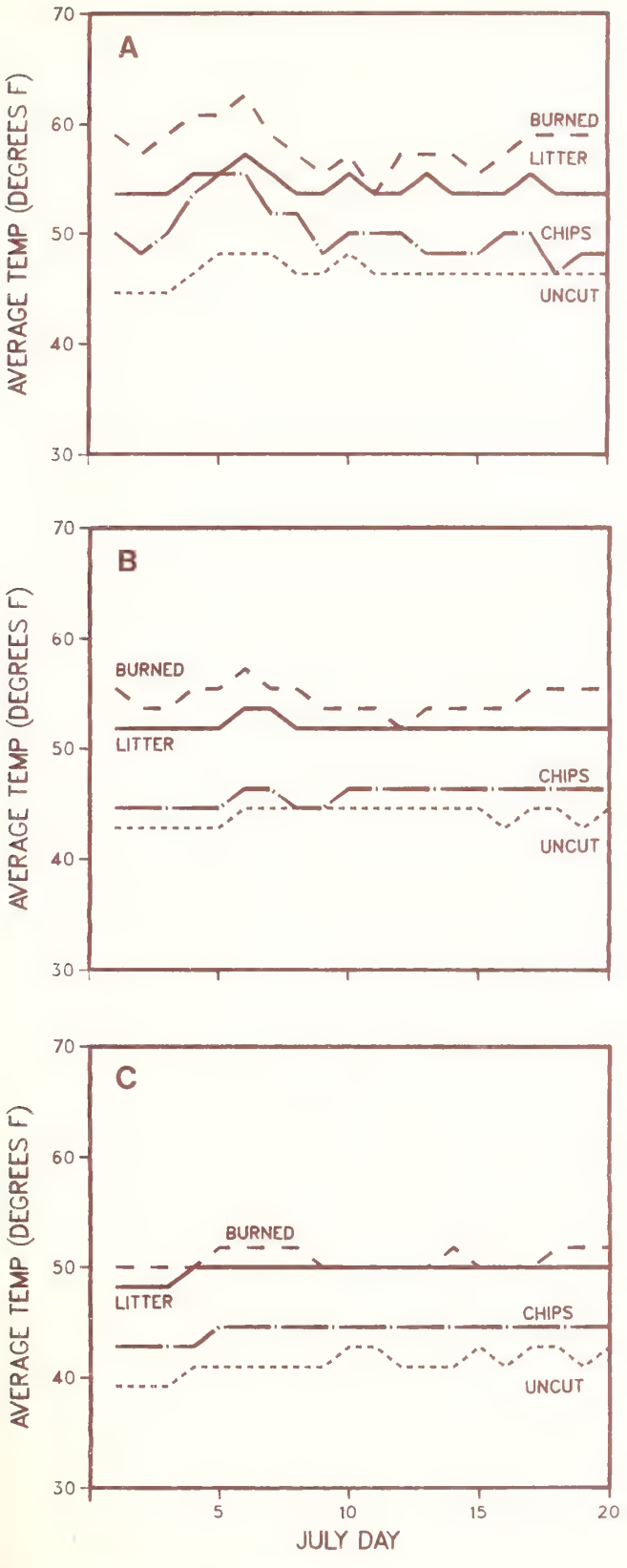


Figure 9—Average soil temperatures at depths of 2 inches (A), 8 inches (B), and 16 inches (C) for burned, litter, and chip surface conditions in clearcut and uncut treatment units. Data are from Union Pass in July 1979.

These results for soil temperature seem to be explained well by the effects of Rn as influenced by overstory removal. Although $\sqrt{KC}$ affects the rate of conduction and associated temperature changes, this factor was overwhelmed by the differences in Rn at the surface of the treatments. These effects will be discussed in more detail for the surface conditions.

SURFACE CONDITION AND TEMPERATURE

Surface conditions resulting from residue treatment included litter, burned, mineral soil, and chips. The effect of surface condition on surface, air, and soil temperatures is examined by comparing temperatures for the different surface conditions under the same overstory treatments. The clearcut was used for all but one comparison. The shelterwood treatment is used in that one.

Surface Temperature

Lubrecht—Maximum surface temperatures on both the burned and litter surfaces in the clearcut were greater than 133 °F during midsummer (fig. 10). For the first 2 years after burning, average maximum (monthly) temperature on the burned surface was 9 to 16 °F greater than on the litter surface. For 57 percent of the months for May through October, these differences were significant. After 2 years, a heavy stand of bull thistle and its thistledown on the burned treatment provided enough shade to decrease surface temperatures below those on the litter surface.

Hot events occurred on the burned and litter surfaces from 17 to 37 percent of the days from May through October (table 6). The HE's were observed for more than 30 days each year after burning on both litter and burned surfaces, even though instrument difficulties resulted in 45 days when temperatures could not be measured.

Minimum temperatures were not significantly different for the burned and the litter surfaces for most months. After the thistle crop developed on the burned treatment, minimum temperatures were significantly warmer on the burned surface than on the litter surface. Both the litter and burned surfaces had significant numbers of CE's in 1979—the first year after burning. Cold events were observed on 42 percent of the days on the litter surface and 26 percent of the days on the burned surface from May through September. Only two CE's were observed on the litter surface in 1980 and none on the burned surface. Climatic conditions and vegetation regrowth were the likely causes of reduced CE's in 1980.

In the shelterwood, average maximum surface temperatures of exposed mineral soil were significantly lower—5 to 34 °F—than temperatures of the litter for 75 percent of the months over the 3 years. Average maximum temperatures on the mineral soil surface never exceeded 100 °F. Difference between the litter and mineral surfaces was least in May and October and greatest in July (fig. 10). Hot events on the litter occurred from 14 to 25 percent of the days, but no HE's occurred on the mineral soil surface during the measurement period. Average minimum temperatures were 1 to 4.5 °F colder on the litter surface

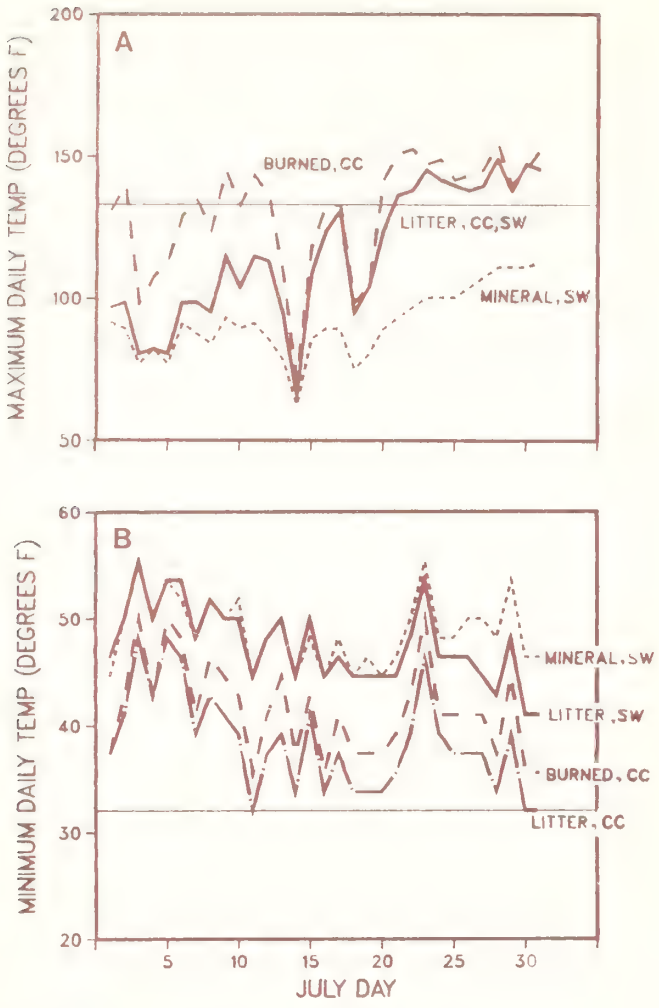


Figure 10—Maximum (A) and minimum (B) daily temperatures of burned, litter, and mineral soil surfaces at Lubrecht in July 1980. Burned surface was measured in the clearcut (cc) and mineral in the shelterwood (sw). Maximum litter temperatures were the same in clearcut and shelterwood. Horizontal line for maximum temperatures (A) is at 133 °F—a seedling survival threshold.

Table 6—Hot events (percentage of possible days) by surface condition at the Lubrecht site. Data are for the months of May through October.

Residue treatment	Years after logging		
	1	2	3
	--- *Percentage of possible days* ---		
Burned surface (clearcut)	—	[1]37	[2]23
Litter surface (clearcut)	27	19	17
Litter surface (shelterwood)	14	16	25
Mineral soil (shelterwood)	0	0	0

[1]First year after burning.
[2]Second year after burning.

than on the mineral soil surface. These differences were significant for only 33 percent of the months. No CE's were observed on the mineral soil or litter surfaces in the shelterwood treatment, mostly because of the overstory canopy. Because the mineral soil surface measured was in the shelterwood treatment, it could not be directly compared to the burned surface in the clearcut; minimums were much warmer in the shelterwood than on the clearcut.

These results indicate a definite contrast between temperatures on organic (burned and litter) surfaces and mineral soil. Because the maximum and minimum temperatures of litter and burned surfaces are similar, the probability of temperature-related seedling mortality may be similar. Lower maximum and higher minimum temperatures on the mineral surface suggest that temperature-related seedling mortality would be lower than on the litter surfaces.

Coram—Only litter and burned surfaces in the clearcut are compared here. From the first through the fourth years after burning, average maximum temperatures on the litter surface were significantly warmer than on the burned surface for 79 percent of the months (May through October). During the fifth and sixth years after burning there were no differences between treatments. Data from another clearcut at Coram, for a shorter period, showed the same results.

Hot events were observed mostly in the first year on the burned surface, and then only on 5 percent of the possible days. The litter surface had 24 to 42 percent of the days with HE's from the first through fourth years. After the fourth year HE's were rare—4 percent or less on the litter surface and only 1 percent on the burned surface.

Minimum temperatures on the burned and litter surfaces at Coram varied from being equal to being 10 °F colder on the litter during the first 4 years after burning. Mean monthly minimum litter surface temperatures were significantly colder for 86 percent of the months by 2.7 to 5.4 °F. Cold events were not observed on either surface for any year.

Union Pass—Burned, litter, and chip surface conditions are compared on the clearcut. Average maximum temperatures were not significantly different between the burned and litter surfaces 6 years after treatment. Hot events were observed on 62 percent of the days for both treatments in July. Maximum temperatures measured on the chip surface were significantly cooler—13 °F—than on the litter or burned surfaces (fig. 11). The HE's were observed 10 percent of the July days on the chip surface.

Average minimum temperature for July was significantly colder on the litter surface than on the burned surface and colder on the chip surface than on either the litter or burned surfaces (fig. 11). Cold events in July were observed on the litter surface 10 percent of the nights, on the chip surface 43 percent, and not at all on the burned surface. These differences in minimum temperatures and CE's are due more to slope position, which demonstrates the effect of cold air drainage (fig. 12).

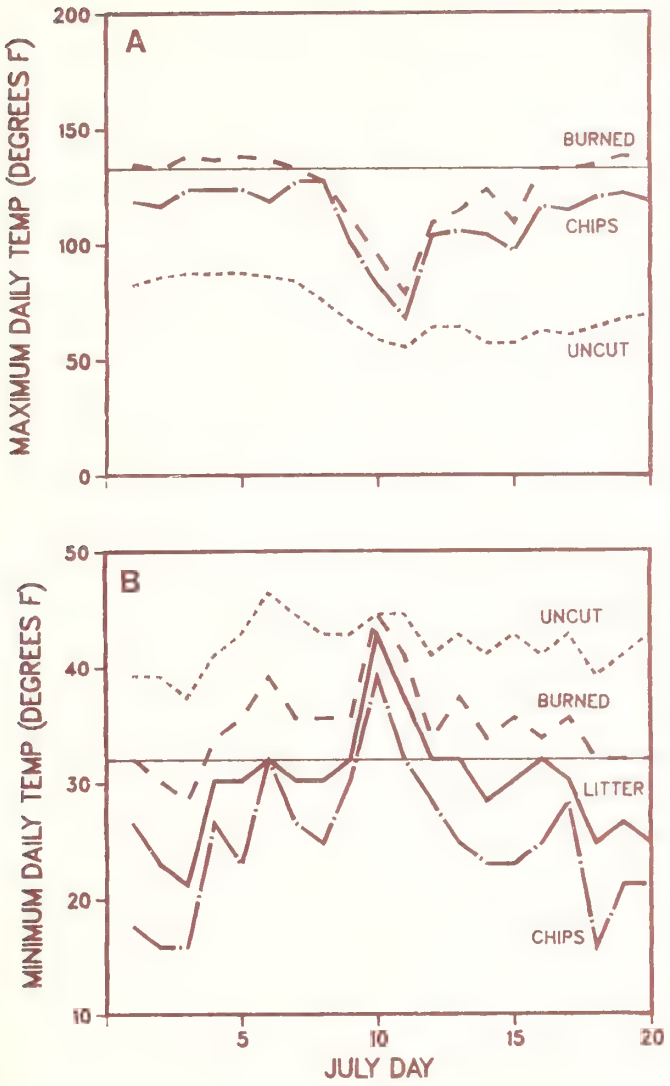


Figure 11—(A) Maximum daily temperatures on burned, chips, and untreated surfaces. Litter surface is same as burned. (B) Minimum daily temperatures on untreated, burned, litter, and chip surfaces. Data are from Union Pass in July 1979. Burned, litter, and chip surfaces are in the clearcut. Horizontal line for maximum temperatures (A) is at 133 °F, a seedling survival threshold.

In summary, the results for Union Pass are consistent with those at Lubrecht for the burned and litter surfaces. Vegetation development for the two treatments is also similar to that at Lubrecht, except slower. Even after 6 years, ground coverage of vegetation was low (less than 25 percent) on both treatments.

The difference in results for maximum temperatures on the burned and litter surfaces between Coram and Lubrecht can be explained by observations about the pretreatment vegetation, subsequent vegetation development, and severity of the burns. At Coram the burn was not as hot as the burn at Lubrecht because of the differences in duff moisture (Artley and others 1978; Steele 1980). This situation, coupled with habitat type differences, promoted rapid postburn vegetation development at Coram. By midsummer of the first year after burning at Coram, a good ground cover of grasses and forbs existed that was quite effective in shading the surface. At Lubrecht the litter surface of the close utilization treatment was disturbed more by ground skidding, which stimulated resprouting and provided conditions for colonization of weeds. At Coram, where a skyline yarder was used, understory vegetation was disturbed differently on the close utilization treatment where the litter surface was measured. Branches and tops of shrubs and herbs were broken and mashed but not severely damaged. As a result, resprouting and regrowth were not stimulated enough to cause rapid growth response, yet coverage was enough to provide a significant number of shaded spots for seedlings.

Comparison With Expected Results—Other published results reveal some inconsistencies between burned and unburned surfaces. Fowler and Helvey (1981) did not find any differences between temperatures on the burned pile, broadcast-burned scarified surfaces, and the unburned surfaces on a clearcut in northeastern Oregon. Ahlgren (1981) reports that burned surfaces were warmer for the first 7 years than were unburned surfaces. After 8 years burned surfaces became cooler, a trend that was attributed to gradual development of shrubs. Our results seem to be consistent with Ahlgren's observation of vegetation development. Temperatures of burned and litter surfaces were similar (both maximums and minimums), yet the amount of vegetation cover and the rate at which it developed significantly modified the differences.

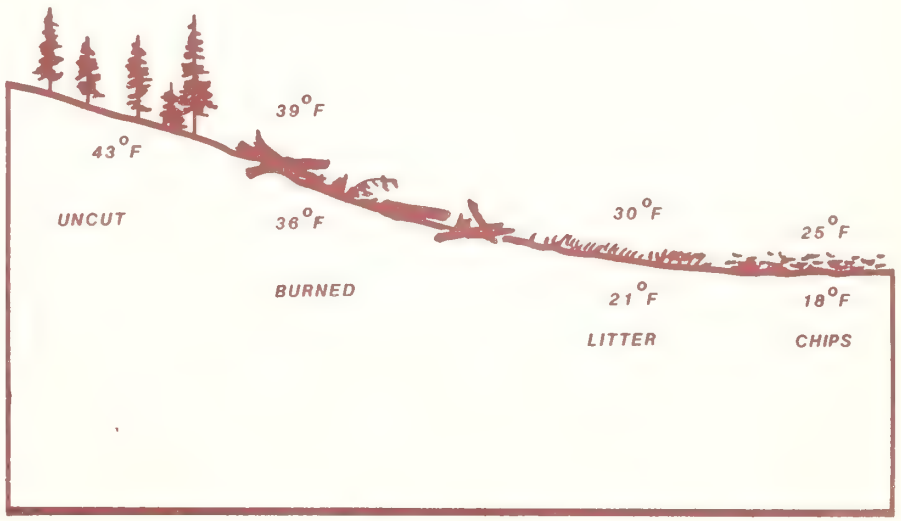


Figure 12—Minimum temperatures at Union Pass on July 10, 1979. The lower row of numbers represents surface temperatures; the upper row represents temperatures at 2 inches above the surface.

Temperatures on the litter and burned surfaces are expected to be similar (under full sunlight), based on the energy balance equation, and the thermal contact coefficient ($\sqrt{KC}$) (table 7) that influences G. This situation applies if we assume that (1) both surfaces are dry, thus the H and LE terms should be equal; and (2) increased Rn contribution to burned surfaces as compared to litter surfaces is offset by a lower $\sqrt{KC}$ value for the litter. This shows that if $\sqrt{KC}$ were different for either surface, because of moisture, compaction, and so forth, the LE term would be different, causing the surfaces to have different temperatures.

The study results reported here, and those published, tend to support the expectation that burned and litter surfaces will be similar. At Coram, however, where maximums on the litter surface were warmer and minimums colder on the burned surface, Rn on the burned surface was apparently reduced by the rapid vegetation growth that provided shade and reduced the temperature variation.

The energy balance equation and thermal properties of $\sqrt{KC}$ (table 7) cause us to expect that temperatures on the burned or litter surfaces will be considerably more variable (higher and lower) than for the mineral soil surface. Lubrecht data are consistent with this expectation. The major factors influencing this difference are $\sqrt{KC}$ and Rn. Net radiation is less on the mineral soil (fig. 13) and $\sqrt{KC}$ is considerably greater for mineral soil than for litter, which means that less heat to the surface is conducted away more quickly than for a litter surface. This keeps the surface temperature from rising as much. The same factors allow heat from the soil to warm the surface at night, which keeps minimum temperatures of mineral soil warmer than litter or burned surfaces. Although mineral soil surfaces in the clearcut were not compared with litter or burned surfaces, the differences should be greater than in the shelterwood. If mineral soil were more moist, the differences would be accentuated even more. LE and $\sqrt{KC}$ would increase for the mineral soil, which would further reduce the temperature variation at the mineral surface in comparison to litter or burned surfaces.

Compared to litter and burned surfaces, the chip surface is expected to have less temperature variation (lower maximums and higher minimums). The data at Union Pass are consistent with this expectation. Chips have a higher albedo, reducing Rn when compared to a litter or burned surface (fig. 13). This lower heat flux density at the surface, coupled with a higher $\sqrt{KC}$ (table 7) than litter or burned surfaces, explains the reduced temperature variation. If the moisture content of the litter surface were higher (relative to the chips), the temperature differences would be reduced because of increased LE, which would lower G.

Figure 14 shows maximum temperatures for four surface conditions compared to air and humus temperatures. The temperatures shown are for a hypothetical site adjusted to a common set of conditions. These are typical maximum summer surface temperatures on a clearcut for a clear day in full sun. Burned and litter surfaces are much warmer than all other surfaces and the humus at a 1-inch depth. All surface conditions are much warmer than air temperature at 4.5 ft.

At Union Pass, minimum temperatures and CE departed from the expected pattern. Litter surfaces were colder than burned surfaces, which should be similar, as at Lubrecht, and the chip surface was colder than either, where it should be warmer (fig. 11B). The basic explanation for these reversals in minimum temperatures lies in the topographic positions of the treatments. The close utilization treatment, where litter surface temperatures were measured, and the chip spread treatment were in a

Table 7—Average values of albedo or reflectivity and the thermal contact coefficient ($\sqrt{KC}$) for typical surfaces. Values are from Fowler (1974).

Surface	Albedo	$\sqrt{KC}$[1]
	Percent	*cal cm^{-2} sec$^{-1/2}$ °C^{-1}*
Burned	2	0.0018
Litter (dry needles)	6-10	.0013
Bark (dry)	20	.0031
Chips	36	.0026
Soil	20-35	.0111
Air	—	.0001
Water	—	.0361

[1] K = thermal conductivity; C = volumetric heat capacity.

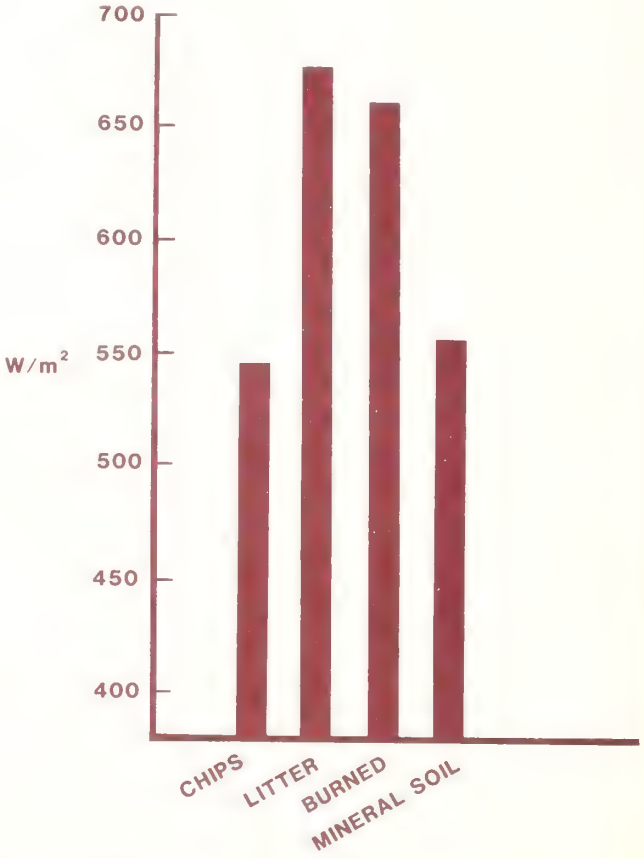


Figure 13—Net radiation over several surface conditions in a clearcut at Union Pass at noon on July 12, 1979. The differences between burned and litter surfaces and between mineral soil and chip surfaces probably are not significant.

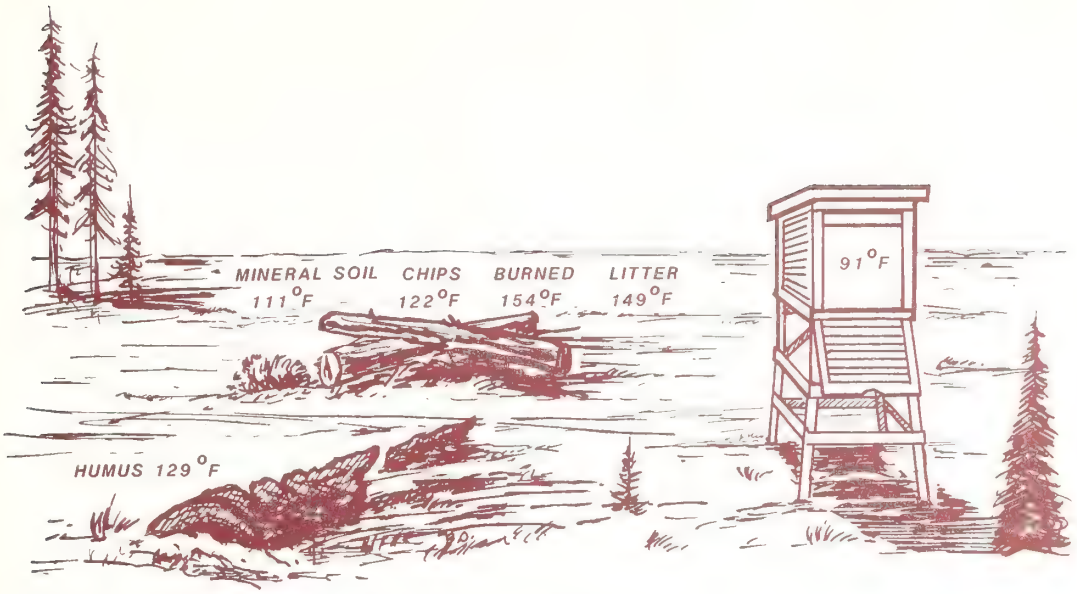


Figure 14—Maximum temperatures expected in a clearcut of a hypothetical site for four surface conditions—burned, litter, mineral soil, and chips—humus at 1-inch depth and air temperature at 4.5 ft.

relatively flat area where cold air accumulates at the toe of a slope that is below the burned surface (fig. 12). The chips treatment is the lowest. In this case H was reduced because of restricted airflow and colder, more dense air accumulated in pockets. This aided radiational cooling, thus lowering the surface temperatures. Additionally, where chips were spread, basins were created in the chips to allow seedlings to be planted. These additional depressions trapped more cold air. Surfaces with lower $\sqrt{KC}$ values are more susceptible to lower temperatures and frosts, particularly in frost-pocket situations.

Air Temperature

Air temperatures above the surface conditions were measured only at Union Pass. Surface condition did not have any effect on maximum air temperature at 4.5 ft or 8 inches above the surface. Because surface temperatures were higher on burned and litter surfaces than on chip surfaces, we expected that air temperatures above these surfaces might be different. However, prevailing winds and upslope thermals likely caused enough mixing that surface differences did not significantly influence maximum temperature at these levels.

Minimum air temperatures were significantly different at both 4.5 ft and 8 inches. Temperatures above the chip surface were significantly colder than above the litter or burned surfaces at both heights. At 8 inches above the litter surface, temperatures were also significantly colder than above the burned surfaces. As with the overstory treatments, these differences are due, at least partially, to cold air drainage caused by slope differences.

Soil Temperature

Temperatures at depths of 2 inches and greater were measured only at Union Pass. Higher surface temperatures of some surface conditions at Union Pass caused greater soil temperatures at depths of 2, 8, and 16 inches. Mean temperatures (at all depths) were significantly warmer below the burned surface than below the litter and chip surfaces (fig. 9). Root zone (2- and 8-inch depths) temperatures ranged from 58.1 to 54.5 °F under the burned surface, 54.3 to 51.8 °F under the litter surface, and 50.1 to 45.5 °F under the chips. Temperatures under the burned and litter surfaces are probably not different enough to cause differences in root growth, plant development, or microorganism activity. The colder temperatures under the chips are likely to decrease root growth, transpiration, and microorganism activity. Temperatures under the chips increase much more slowly in the growing season than under the other surfaces. Near-freezing temperatures and frost were often observed in June under the chips. Spreading the chips shortened an already short growing season at this high elevation.

Summary

Temperatures at the ground surface, to depths of 16 inches, are warmer for burned and litter surface conditions than for mineral and chip surface conditions. The results are explained rather well by the energy balance equation and the thermal properties of the surfaces. Differences in temperature between the burned and litter surfaces seem to be influenced by the rate of vegetation recovery. This is consistent with other published results. Minimum temperature differences departed from the expected pattern due to slope position that affects cold air drainage. Differences in the soil mimic the differences at the surface for the surface conditions studied.

Surface condition does not appear to influence air temperature. Wind movement likely caused enough mixing to mask any differences in maximum temperature. Differences in minimum air temperatures are apparently caused by differences in slope position.

REGENERATION RESPONSE

Assuming that HE's and CE's are events with a potential for causing seedling mortality, there should be a relationship between these events and actual seedling survival. For the sites in this study, the relationship between HE's and CE's and regeneration success does seem to be strong and consistent.

Lubrecht

At Lubrecht, the frequency of HE's and CE's (table 8) suggests that first-year survival should be lower on the clearcut than on the understory removal for the first 2 years. Douglas-fir and western larch survival (first year) for the 1979 planting was from 0 to 8 percent (table 8) on the clearcut treatment, and greater than 64 percent on the understory removal treatment where no HE's or CE's were measured (Schmidt 1984).

Survival for ponderosa pine was greater than for Douglas-fir or western larch at about 50 percent on the clearcut and 96 percent on the understory removal treatment. Even though the survival was higher for ponderosa pine, the pattern of survival for all species was consistent with the expected pattern, based on HE's and CE's.

First-year survival for seedlings of all species planted in 1980 was higher than for the 1979 planting, which might be expected because the number of HE's and CE's was lower than for 1979. The clearcut had the highest frequency of HE's and CE's and much lower survival for western larch than for the understory removal. Survival differences were not as dramatic as the previous year for Douglas-fir. Survival of ponderosa pine was not much different for any of the treatments except the close utilization surface in the clearcut. Overall, for all species in both years, survival was not different between the broadcast burn and close utilization treatment, which is consistent with the pattern of HE's and CE's.

The frequency of HE's during the growing season seems to better explain the pattern of survival for western larch than do the CE's. For ponderosa pine, CE's seem to better explain the pattern of survival than the HE's. For Douglas-fir, HE's and CE's seem to be about equal in explaining the survival pattern. These results are consistent with our ideas about the adaptability of these three species. Ponderosa pine is known to be more adapted to hot-dry sites and thus may survive the HE's better than the CE's. Douglas-fir, the intermediate of these species, is better adapted to drier sites than is western larch but not as well as ponderosa pine, thus possibly being equally susceptible to HE's and CE's at Lubrecht. Western larch would be expected to be more sensitive to hot-dry sites. Thus, the mortality would likely be the result of the HE's and related moisture stress before the CE's occurred.

Coram

The only two comparisons at Coram that can be made are between the burned surface of the broadcast burn treatment and the litter surface of the close utilization treatment within the clearcut. Seedling survival was high (90 percent) on both treatments for all plantings (Shearer 1980) of Douglas-fir and Engelmann spruce even though HE's were more frequent on the litter surface. Hot events on the litter surface were nearly as frequent as at Lubrecht, but they were rare on the burned surface after the first year. In both treatments at Coram there was more vegetation and debris to provide protection for seedlings than at Lubrecht. Germination and survival on the seeded spots were higher on the burned surface than on the litter surface. The HE's likely had minimal effect on survival of germinating seedlings, but insufficient moisture was the major cause of mortality (Shearer 1980). However, moisture was less of a limiting factor at Coram than at Lubrecht. The absence of CE's seems to have benefited seedling survival at Coram.

Table 8—First-year plantation survival data from Lubrecht for ponderosa pine, Douglas-fir, and western larch container stock planted on clearcut and understory removal treatments. Broadcast burn and close utilization treatments were used in the clearcut. Hot events and cold events for these treatments are shown by year.

	Clearcut		
	Broadcast burn[1]	Residue removed[2]	Understory removal[2]
	1979		
Species (percentage survival)			
Ponderosa pine	48	28	96
Douglas-fir	4	8	76
Western larch	4	0	64
Temperature (percentage days)			
Hot events	37	19	0
Cold events	26	42	0
	1980		
Species (percentage survival)			
Ponderosa pine	100	60	84
Douglas-fir	52	56	72
Western larch	8	16	68
Temperature (percentage days)			
Hot events	23	17	0
Cold events	0	3	0

[1]Surface condition was burned.
[2]Surface condition was mostly litter.

Union Pass

At Union Pass, seedling survival after 5 years was 92 percent on the broadcast burn treatment, 46 percent on the close utilization treatment, and 26 percent on the chip spread treatment in the clearcut (Schmidt 1982). Survival for each of these treatments is more closely related to CE's (table 9). The HE's apparently did not influence survival. The CE's and survival seem to be related to the topographic position of the treatments in a frost pocket rather than to the surface conditions themselves. Stocking on the seed spots and natural regeneration spots also decreased as the frequency of CE's increased.

Summary

In general, probability of seedling survival increased whenever the frequency of HE's and CE's decreased. It appears likely that CE's caused freezing of plant tissue, which contributed to seedling mortality. For HE's, the damage may have been a direct heat injury that caused death, but it is just as likely that the high temperatures caused dessication of the soil, creating moisture stress

Table 9—Plantation survival data after 5 years (1982) for lodgepole pine at Union Pass, WY, on a clearcut with three residue treatments. Hot and cold events are given for July 1979.

	Clearcut		
	Broadcast burn[1]	Close utilization	Chips
Species (percentage survival)			
Lodgepole pine	96	46	26
Temperature (percentage days)			
Hot events	62	62	10
Cold events	0	10	43

[1]Temperatures were measured on the burned surface on the broadcast burn, litter surface on the residue removed, and the chip surface on the chips.

conditions that led to seedling mortality. Higher radiation loads on the seedlings in the clearcut and above some surface treatments, such as the chips, caused the elevated surface and soil temperatures and also greater vapor pressure deficits (increased LE) and thus greater moisture stress in the seedlings.

Imposing treatment practices to reduce temperature variation must be used with caution. Treatments that have been shown to reduce temperature variation (exposing mineral soil) also increase evaporation and can create a moisture deficiency problem. On sites where high temperature is not a problem but moisture is, leaving a mulch (litter) or providing one may reduce moisture losses (Cochran 1969). Another major factor is the condition of planting stock. At Lubrecht, condition of the containerized seedlings was quite variable (Shearer 1985). Seedlings that are already stressed may be more likely to succumb when planted in more stressful situations. Thus, these results do not provide proof of the relationship between temperature and mortality. But they do provide strong evidence that the effects of treatment on site energy balance and thermal properties should be evaluated in relationship to the potential for seedling survival.

CONCLUSIONS AND IMPLICATIONS FOR MANAGERS

Several points from this and other studies have a bearing on surface temperature modification and successful regeneration of stands.

1. It is crucial to be able to identify potential mortality problems due to temperature and moisture at the time silvicultural prescriptions are prepared. If problems are expected, steps can be taken to avoid problems by altering silvicultural and subsequent reforestation practices.

2. Current reforestation guides indicate that high temperatures are a problem on south and west aspects on slopes over 30 percent at lower elevations. In this study, potentially lethal high temperatures were also observed on level ground, on east-facing slopes, and at high elevations on clearcuts in Douglas-fir and subalpine fir habitat types. Potentially lethal cold temperatures were measured on level sites at high and low elevations in both habitat series. The pattern of seedling survival on these sites indicates that mortality was in fact related to the hot and cold temperature events.

3. Results of this study show that shelterwood or partial cuttings with 50 percent or less sunlight transmission to the forest floor significantly reduce the occurrence of high temperatures and low temperatures. Seedling survival was higher in these stands.

4. Seedbed preparation and residue treatments for slash reduction significantly influence the occurrence of potentially lethal seedbed surface temperatures by altering the thermal properties of the surface. In general, practices that increase the thermal conductivity and volumetric heat capacity (thus, $\sqrt{KC}$—thermal contact coefficient) of the surface materials will decrease maximum temperatures and increase minimum temperatures. Treatments that expose mineral soil reduce surface temperature variation (decrease maximum and increase minimum) compared to natural litter-covered surfaces. Burned and natural litter-covered surfaces on clearcuts may be equally susceptible to high temperatures, based on results reported here. However, this may vary depending on the thermal properties of the surface materials.

5. Where it is not practical to alter the surface materials (thermal properties), excessively high and low temperatures can be reduced by providing shade. Leaving enough residues onsite to provide adequate shade protection will reduce temperatures and increase seedling survival. Residues can also conserve moisture at the surface by reducing evaporation. Allowing some vegetation growth (provided moisture is not limiting) will also provide adequate shade and thus temperature modification. Seedlings planted on these sites should be positioned to take advantage of the modified microsites—on the north or east sides of logs, stumps, branches, rocks, etc.

6. On sites where soil moisture is more of a problem than is high temperature, mulches (plant litter, artificial materials; dry, loosened soil; etc.) left on the surface can help retard evaporation and thus increase survival. However, these practices must be planned carefully because they will increase surface temperatures.

7. Frost-pocket problems can be aggravated by overstory and residue treatment. The ability to identify potential frost pockets while developing the silvicultural prescription is important. Subalpine fir in drainages or flat areas or *Vaccinium caespitosum* in the understory are often good indicators of potential frost pockets.

8. Shade from partial overstories, residue, or understory vegetation can provide varying degrees of protection for seedlings in frost pockets. Only the most frost-resistant species should be used in frost-pocket areas.

9. Clearcuts and other cutting units should be laid out to provide for adequate air drainage through a cutting unit, if it is not the lowest depression. This will minimize cutting-related frost pockets. Smaller cutting units (group selections) will reduce radiational cooling and frost problems on sites that may have potential problems. To be effective, widths of strips or patches should be less than two tree (border tree) heights wide.

REFERENCES

Ahlgren, Clifford E. Seventeen-year changes in climatic elements following prescribed burning. Forest Science. 27(1): 33-39; 1981.

Artley, Donald K.; Shearer, Raymond C.; Steele, Robert W. Effects of burning moist fuels on seedbed preparation in cutover western larch forests. Research Paper INT-211. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1978. 14 p.

Baker, Frederick S. Effect of excessively high temperatures on coniferous reproduction. Journal of Forestry. 27: 949-975; 1929.

Benson, Robert E. Management consequences of alternative harvesting and residue treatment practices—lodgepole pine. General Technical Report INT-132. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. 58 p.

Cleary, D. D.; Waring, R. H. Temperature: collection of data and its analysis for the interpretation of plant growth and distribution. Canadian Journal of Botany. 47: 167-173; 1969.

Cochran, P. H. Thermal properties and surface temperatures of seedbeds: a guide for foresters. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1969. 19 p.

Cochran, P. H. Soil temperatures and natural forest regeneration in south-central Oregon. In: Bernier, B.; Winget, C. H., eds. Forest soils and land management: Proceedings of the fourth North American forest soil conference; 1973. Quebec, PQ: Laval University; 1975: 37-52.

Cochran, P. H.; Bernsten, Carl M. Tolerance of lodgepole and ponderosa pine seedlings to low night temperatures. Forest Science. 19(4): 172-280; 1973.

Edgren, James W.; Stein, William I. Artificial regeneration. In: Cramer, Owen P., ed. Environmental effects of forest residues management in the Pacific Northwest: a state of knowledge compendium. General Technical Report PNW-24. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1974: M1-M32.

Fowler, W. B. Microclimate. In: Cramer, Owen P., ed. Environmental effects of forest residues management in the Pacific Northwest: a state of knowledge compendium. General Technical Report PNW-24. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1974: N1-N18.

Fowler, W. B.; Helvey, J. D. Soil and air temperature and biomass after residue treatment. Research Note PNW-383. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1981. 8 p.

Gates, David M. Biophysical ecology. New York: Springer-Verlag; 1980. 611 p.

Hallin, William E. Soil surface temperatures on cutovers in southwest Oregon. Research Note PNW-78. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1968. 17 p.

Hare, Robert C. Heat effects on living plants. Occasional Paper 183. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station; 1961. 32 p.

Hellmers, H.; Genthe, M. K.; Ronco, F. Temperature affects growth and development of Engelmann spruce. Forest Science. 16(4): 447-452; 1970.

Hungerford, Roger D.; Schlieter, Joyce A. Weather summaries for Coram Experimental Forest, northwestern Montana—an International Biosphere Reserve. General Technical Report INT-160. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1984. 34 p.

Kramer, Paul J.; Kozlowski, Theodore T. Physiology of woody plants. New York: Academic Press; 1979. 811 p.

Levitt, J. Responses of plants to environmental stresses. 2d ed. New York: Academic Press; 1980. 497 p.

Lotan, James E. Initial germination and survival of lodgepole pine on prepared seedbeds. Research Note INT-29. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1964. 8 p.

Lotan, James E.; Perry, David A. Ecology and regeneration of lodgepole pine. Agriculture Handbook 606. Washington, DC: U.S. Department of Agriculture, Forest Service; 1983. 51 p.

Montana Forest and Conservation Experiment Station. Weather data summary 1956-1982: Lubrecht Experimental Forest, Greenough, Montana. Missoula, MT: University of Montana, School of Forestry; 1983. 28 p.

Pfister, Robert D.; Kovalchik, Bernard L.; Arno, Stephen F.; Presby, Richard C. Forest habitat types of Montana. General Technical Report INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1977. 174 p.

Rose, C. W. Agricultural physics. 1st ed. Long Island City, NY: Pergamon; 1966. 226 p.

Ryker, Russell A.; Potter, Dale R. Shade increases first-year survival of Douglas-fir seedlings. Research Note INT-119. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1970. 6 p.

Schmidt, Jack. [Personal communication]. 1984. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, Missoula, MT.

Schmidt, Wyman C. Regeneration and growth of conifers. In: Benson, Robert E. Management consequences of alternative harvesting and residue treatment practices—

lodgepole pine. General Technical Report INT-132. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982: 18-23.
Shearer, Raymond C. Insolation limits initial establishment of western larch seedlings. Research Note INT-64. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1967. 8 p.
Shearer, Raymond C. Regeneration establishment in response to harvesting and residue management in a western larch—Douglas-fir forest. In: Environmental consequences of timber harvesting in Rocky Mountain coniferous forests: Proceedings of the symposium; 1979 September 11-13; Missoula, MT. General Technical Report INT-90. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980: 249-269.
Shearer, Raymond C. Silviculture. In: DeByle, Norbert V. Clearcutting and fire in the larch/Douglas-fir forests of western Montana—a multifaceted research summary. General Technical Report INT-99. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1981: 27-31.
Shearer, Raymond C. [Personal communication]. 1985. U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, Missoula, MT.
Silen, Roy R. Lethal surface-temperatures and their interpretation for Douglas-fir. Corvallis, OR: Oregon State University; 1960. 170 p. Ph.D. dissertation.
Steele, Robert W. Postharvest residue burning under alternative silvicultural practices. Research Note INT-293. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1980. 7 p.
Steele, Robert; Cooper, Stephen V.; Ondov, David M.; [and others]. Forest habitat types of eastern Idaho-western Wyoming. General Technical Report INT-144. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 122 p.
Strothman, Rudolph O. Douglas-fir in northern California: effects of shade on germination, survival and growth. Research Paper PSW-84. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; 1972. 10 p.
van Wijk, W. R.; DeVries, D. A. Periodic temperature variations in a homogeneous soil. In: van Wijk, W. R. Physics of plant environment. 2d ed. New York: John Wiley and Sons; 1966: 102-143.

☆U.S. GOVERNMENT PRINTING OFFICE:1987- 773-039/41039

Hungerford, Roger D.; Babbitt, Ronald E. Overstory removal and residue treatments affect soil surface, air, and soil temperature: implications for seedling survival. Research Paper INT-377. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1987. 19 p.

Potentially lethal ground surface temperatures were measured at three locations in the Northern Rocky Mountains but occurred more frequently under treatments with greater overstory removal. Observed maximum and minimum temperatures of exposed surfaces are directly related to the thermal properties of the surface materials. Survival of planted seedlings was consistent with the pattern of potentially lethal temperatures. Care in manipulating overstory canopies and residues can enhance the potential for tree seedling survival.

KEYWORDS: temperature, seedling survival, timber harvesting, thermal properties

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

United States
Department of
Agriculture

Forest Service

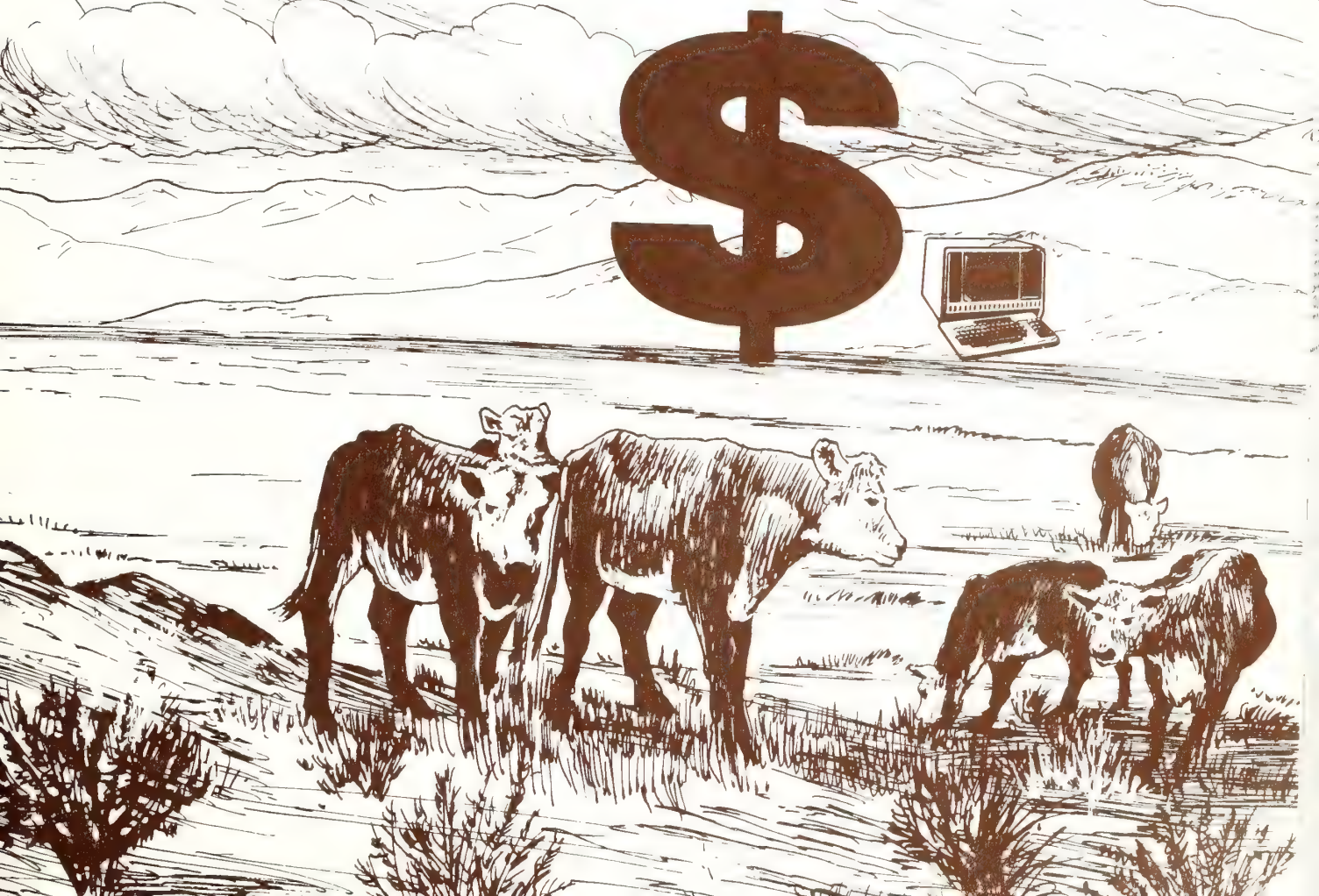
**Intermountain
Research Station**

Research Paper
INT-378

Finding the Appropriate Forage Value for Analyzing the Feasibility of Public Range Improvements

Fred J. Wagstaff
C. Arden Pope III

...SON UNIVERSITY



RESEARCH SUMMARY

To complete economic analysis of range improvements completed on the Oak Creek Management area of central Utah, we needed an estimate of the value of forage. A review of the literature revealed several methods of estimating forage values. These methods yielded eight estimates of public rangeland forage ranging from $1.23 to $30 per animal unit month (AUM). Six of the estimates were based on actual market transactions or current administered prices and were the most reflective of actual economic processes. The best estimates of value were those for leasing similar rangeland in the immediate area.

THE AUTHORS

FRED J. WAGSTAFF is a range economist with the Intermountain Research Station, Shrub Sciences Laboratory, Forest Service, U.S. Department of Agriculture, Provo, UT. He received his Ph.D. degree in range and wildlife science at Brigham Young University in 1983. He has served in the Forest Service in various planning and administrative capacities for approximately 20 years. He has conducted research primarily relating to range and resource economics.

C. ARDEN POPE III is an associate professor of agricultural and resource economics at Brigham Young University, Provo, UT. He received his Ph.D. degree in agricultural economics from Iowa State University in 1981. Previously, he worked as a research associate and staff economist for the Center for Agricultural and Rural Development, and as an assistant professor of agricultural economics at Texas A. & M. University. He has conducted and published research findings dealing with a broad range of issues and topics relating to production and natural resource economics.

May 1987

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Finding the Appropriate Forage Value for Analyzing the Feasibility of Public Range Improvements

Fred J. Wagstaff
C. Arden Pope III

INTRODUCTION

The concern about finding the value of range forage on public lands has been with us for many years. The Federal Government has long been concerned with determination of grazing fees that represent or are based on fair market values (Sutton 1983; Andrus and Berglund 1977). The search for the most appropriate value estimate for public land grazing has led to many studies throughout the years using different approaches and resulting in a multitude of recommendations (Clawson 1938; Vass 1940; Roberts 1963, 1967; Nielsen 1972; Bartlett 1983). The results of these evaluation studies have been tempered by the political process involved in grazing fee determination and have resulted in an administrative fee based largely on political compromises that generally underestimate the value of public land grazing benefits.

Using an appropriate level of forage value or benefit is crucial in economic analysis because use of unsupported and unrealistic values casts doubt on the validity of the conclusions. Currently, there is considerable variation in the values used for planning and analysis purposes even within a single agency (USDA 1982). Brown (1984) points out there are numerous assumptions to any method of determining values, and "the value" probably does not exist. Viewing forage from a static value concept differs from a standard economic theory where values are continually fluctuating around a dynamic equilibrium due to supply and demand forces (Watson and Holman 1977).

Economic analysis of range improvement practices and comparison of alternative uses for rangeland require reasonable and appropriate estimates of the value of livestock grazing benefits. These estimates, however, differ greatly depending upon the methodology used and the critical assumptions made. This paper will briefly discuss the most common approaches to valuing livestock grazing on public lands. The variability of their results is demonstrated in a case study based on the Oak Creek Range Evaluation Project in central Utah (Pope and Wagstaff 1987).

EVALUATION METHODS

Currently, the forage value that is used to establish the grazing fees charged by the Bureau of Land Management (BLM) and Forest Service is based on a predetermined formula. This formula consists of a base value of $1.23 per animal unit month (AUM) and is adjusted annually based upon charges in private grazing leases, value of beef cattle, and the cost of production. The base value of $1.23 is based on a market rental survey of leases of forage from 1964 to 1968. In 1985, grazing fees were set at $1.35, and based on this formula, grazing fees in 1986 would be about $1.01. A recent executive order by President Reagan maintains the current fee formula but sets a floor of $1.35 per AUM. The Federal lands grazing fee has not been set at a level reflecting full market value in the past, nor does it appear this will happen in the near future. The practice of underpricing has caused the grazing permits to take on value through capitalization of the surplus.

Budgeting Procedures

Several methods of ranch firm or enterprise budgeting can be used to estimate the value of forage. These methods range from hand-driven itemizations of firm expenses and income to highly complex computerized linear programming models. Recent publications by the Economic Research Service show the results of applying linear programming in Western States (Gee 1981, 1983). Values obtained from linear programming studies where producer estimates of values are grouped are consistently, and often considerably, higher than the results of other methods. This probably reflects the results of using small samples of producers and the fact that other methods underestimate the full value of forage in the production process.

The budgeting approach to estimating value has appeal because of the straightforward procedure, but it rests on several assumptions that need to be understood. The budget approach depends upon the correct allocation of income and expenses to many variables used in a livestock firm, and without large amounts of expense and accounting data it is questionable (Bartlett 1983). During times of rapid factor price change, budgeting may be seriously deficient as an estimator of value.

Major criticism and questioning of the validity has come from many authors. They basically argue that it is highly questionable to allocate residual income to a single factor such as grazing forage (Gee 1983). Indeed, to arbitrarily price management and unpaid family labor at some prescribed level and then allocate remaining value to another factor seems highly questionable.

In practice, budgeting can be used to give some rapid first approximations of values and as a check on other methods. Because budgets require considerable data, many

analysts rely on secondary sources for many items and supplement this with primary data. This tends to decrease accuracy of results.

Substitute Feed Method

Economic theory holds that if two factors are perfect substitutes for each other in a production process and the value of one is known, the value of the other in the process is set at the same level (Watson and Holman 1977). There have been attempts to value range forage by this approach (Roberts 1967; Bartlett 1983). In these studies, relatively high values were derived due to the strict assumptions of the model.

The substitute feed approach rests upon determining a price for the substitute, which is commonly hay because market prices are recorded. This price then must be adjusted for quality differences, location, and other costs incurred in using the substitute, and considerable judgment is required as well as some assumptions concerning the practicality and feasibility of such a practice (Wagstaff 1983).

Market Comparisons

Several studies conclude that there is an established market for public range forage and that the value of forage can be determined through market analysis (Gardner 1962; Bartlett and others 1981; Bartlett 1983).

Estimates of value are made by comparing the item in question to the value or price for which similar items have been exchanged. The larger the number of market transactions and the more homogeneous the item, the more reliable estimates will be. Range forage is location specific: livestock must be moved to where the forage is. Also, certain ranges have climatic attributes that allow use only during a specific season.

If a range forage market does exist and public land forage is traded in that market as argued by Nielsen and Wennergren (1970), Bartlett (1983), Gardner (1962), and Roberts (1967), then exchange price could be used to estimate value. It is true that adjustments must be made and care exercised to compare transactions that are as similar as possible to the subject area.

The literature details two approaches to market comparisons. One approach uses sales of forage itself through rents or leases with required adjustments. The other approach uses the capitalized value of Federal grazing permit transfers between individuals.

Federal grazing permits have value due to the fee being set at a level below the value of the forage to livestock owners. These permits are bought and sold even though they are not recognized as a vested right by the issuing agencies (Andrus and Berglund 1977; USDA and USDI 1985). The annualized value of this permit plus the fee and nonfee costs will yield an estimate of the willingness to pay value of the forage.

Case Example

In 1978, the Oak Creek Range Management Project was established under an accelerated range management program spearheaded by the Forest Service (Pope and Wagstaff 1987). The project included 117,200 acres of the Fillmore District of Fishlake National Forest in central Utah. Economic analyses were to be completed for various practices and improvements. An integral part of these analyses was a reasonable estimate of the value of public rangeland forage for livestock grazing.

Eight estimates of AUM values on the Oak Creek Project Area are provided in table 1. These estimates have resulted from different studies using alternative methods.

Table 1—Animal unit month (AUM) value for the Oak Creek Range Management Area

Method	AUM value
1. Grazing fee from current formula (1985)[1]	$ 1.35
2. Budgeting/linear programming (1981)[2]	9.46
3. Substitute feed (hay)	30.00
4. Substitute feed (irrigated pasture-hay meadow)	15.00
5. Market comparison (private rangeland lease rate, 1983)[1]	5.50
6. Market comparison (private rangeland lease rate, adjusted for cost and advance payment 1983)[1]	4.68
7. Market comparison (annualized average permit value plus grazing fee)[3]	5.93
8. Market comparison (competitive bid on comparable State land, 1982-1985 average)	6.23

[1]See USDA and USDI "1985 Grazing Fee Review and Evaluation."
[2]See Gee 1981.
[3]Average permit value from table 2. Annualization rate equals 8 percent (57.29 × 0.08 + 1.35).

Estimate 1 is the grazing fee for 1985 established by the current public rangeland grazing fee formula. Because the indices upon which this fee is determined have not proven highly reliable, and political considerations have held the fee at levels different from those shown by the indexing, the fee as an estimate of full forage value for livestock production is unreliable. This estimate of value is an average value and would be low as an estimate of additional forage value.

Estimate 2 comes from budget/linear programming. The figure is from an Economic Research Service (ERS) study using linear programming to estimate forage value (Gee 1981). The AUM value of $9.46 is basically the estimated residual income to the forage as determined by this approach. This value may reflect the higher end of values because a panel of producers generated the coefficient for the budgets, and they probably reflect a higher than average efficiency in livestock production.

Estimates 3 and 4 are based upon the substitute feed approach. This approach is highly questionable and results

in crude estimates. These estimates exaggerate the value of forage due to the shortage of substitute feed in the form of hay and the high prices of hay due to strong demand from the California dairy industry and export to Japan. Hay prices in 1983 and 1984 were $76 and $73 per ton, so the use of hay to produce feeder calves is clearly not reasonable because this would be roughly $30 per AUM, and other feed sources would be cheaper.

Irrigated pasture is limited and rents for about $15 per AUM. Also, comparability is a problem in using either hay or irrigated pasture to value range forage because animal performance, services included, and other factors differ greatly from public rangeland.

Estimates 5 through 8 are estimates of AUM values that resulted from actual market comparisons. They are also measures of the value for substitute forage. Estimates 5 and 6 are based on private rangeland lease rates as reported in the 1985 Grazing Fee Review and Evaluation (USDA and USDI 1985). Estimate 6 is adjusted for additional costs associated with grazing on public land and a prepayment adjustment.

Estimates 7 and 8 are based on data more specific to the Oak Creek Project Area. To obtain estimate 7, information was obtained on all transfers of grazing permits on the Fillmore District that occurred from 1978 through June 1985. These were transfers of permits on National Forest lands within or directly surrounding the project area. In this period, 38 transfers occurred. During 1985, buyers of these permits were contacted to establish the actual amount paid for the permits alone. Of the 38 transfers, there were 24 bonafide transactions in which the permits were actually bought and sold and the price paid for the permits could be verified. All 24 transactions involved only the permit and cattle. On nine of the transfers the price of the permit could not be verified because the whole ranch was sold with no reliable breakdown of price cost of permits, the buyer couldn't remember or didn't know the breakdown between cows and permits, or the transaction occurred between family members at a "less than arms length" transaction. Five of the buyers could not be contacted. All of the ranchers contacted willingly verified the transactions and provided the price paid for permits.

The price paid for permits on an AUM basis ranged from $29.70 to $95.45 with an average of $57.29. The average prices paid for permits on an AUM basis for 1978 through 1985 are given in table 2. These compare closely with 1983 public permit values in Utah as observed in the "1985 Grazing Fee Review and Evaluation" (USDA and USDI 1985). The value was annualized assuming a perpetual interest in the permit, using an 8 percent interest rate and added to the annual grazing fee.

To obtain estimate 8, prices for grazing on State of Utah Division of Wildlife Resources land were obtained. State lands, similar to those in the project area that are included in an open bidding process, are used to calculate average bid prices for each year. A large tract of land managed by the State of Utah lies adjacent to the southeast of the development area. It is similar in topography and vegetation, is used during the same season, and

Table 2—Summary of permit transfers, Fillmore Ranger District, Fishlake National Forest, 1978 to 1985

Record number	Year	Number of cattle	AUM's	$/AUM
1	1985	8	28	38.57
2	1982	30	110	88.64
3	1978	22	77	42.86
4	1981	15	52.5	38.57
5	1984	17	40.23	42.25
6	1984	17	40.23	42.25
7	1978	241	1,164.83	41.38
8	1980	48	152	55.26
9	1979	49	155.18	55.26
10	1982	48	232	62.07
11	1980	50	183.33	47.74
12	1984	17	57.23	29.70
13	1983	87	304.5	57.14
14	1982	36	174	62.07
15	1982	40	193.33	62.07
16	1981	34	164.33	82.76
17	1985	10	48.33	62.07
18	1978	20	97.67	62.07
19	1979	15	50.5	29.70
20	1979	72	264	75.00
21	1983	52	190.67	95.45
22	1983	20	73.33	95.45
23	1984	20	73.33	95.45
24	1983	34	164.33	51.72
Totals		1,002	4,090.85	57.29

leasees have essentially the same responsibility for livestock care and management as on adjoining Federal lands. Its lease rate is the average bid rate for all State Division of Wildlife Resources grazing land leases for the previous year. A summary of average lease rates or bids for 8 years is shown in table 3.

Table 3—Grazing lease information for lands administered by Utah Division of Wildlife Resources, 1978 to 1985

Year	AUM's	Average lease or bid	Change from previous year
		Dollars	*Percent*
1978	3,846	5.28	—
1979	4,367	4.75	−10
1980	3,902	4.27	−10
1981	3,129	5.44	+27
1982	3,864	6.23	+14.5
1983	3,841	5.71	−8
1984	4,015	6.57	+15
1985	7,336	6.41	−2.5
Average, 1983 to 1986:		6.23	

CONCLUSION

Evidently, estimates of forage value differ significantly depending upon the methodology and assumptions used. However, the most realistic value estimate seems to be determined through market comparisons of the most likely substitute forage. Such an estimate is based on what producers actually pay, not what they hypothetically could or should pay.

This study suggests that a reasonable estimate of the market value of public range forage in the Oak Creek area falls within the $4.50 to $6.50 range. Economics analysis of range improvements should consider the sensitivity of the analysis results to charges in forage values.

The feasibility analysis of public range improvements will be most accurate if forage values derived from market transactions are used or they are most reflective of actual conditions. Rough estimates from other methods could be used for a quick estimate, and then a sensitivity analysis can be used to show how much effort is justified in getting a better estimate. The value of the fee and the linear programming studies could be used as high and low brackets for first estimates of forage value.

In the case example, the selection of a forage value, with the exception of the value of hay as a substitute feed, confirms this conclusion. The project costs per additional AUM of forage produced were quite high (see Pope and Wagstaff 1987).

REFERENCES

Andrus, C. D.; Berglund, B. Study of fees for grazing livestock on Federal lands. Washington, DC: U.S. Government Printing Office; 1977. 303 p.

Bartlett, E. T. Valuing range forage on public rangelands. In: Wagstaff, F. J., compiler. Proceedings—range economics symposium and workshop; 1982 August 31-September 2; Salt Lake City, UT. Gen. Tech. Rep. INT-149. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Research Experiment Station; 1983: 92-100.

Bartlett, E. T.; Kehmier, P.; Taylor, R. G. Valuation and demand for U.S. Forest Service grazing in Colorado: a report prepared for the Forest Service. Colorado State University, Fort Collins, CO: Department of Range Science; 1981. 62 p.

Beale, D. M.; Smith, A. D. Forage use, water consumption, and productivity of pronghorn antelope in western Utah. Journal of Wildlife Management. 34: 570-582; 1970.

Brown, T. C. The concept of value in resource allocation. Land Economics. 60(3): 231-241; 1984.

Clary, W. P.; Beale, D. M. Pronghorn reactions to winter sheep grazing, plant communities, and topography in the Great Basin. Journal of Range Management. 36: 749-752; 1983.

Clawson, M. Determination of sales and lease values of private and public range lands. Journal of Farm Economics. 20: 641-651; 1938.

Foss, P. O. The determination of grazing fees on federally-owned range lands. Journal of Farm Economics. 41(3): 535-546; 1959.

Gardner, B. D. Transfer restrictions and misallocation in grazing public range. Journal of Farm Economics. 44(1): 50-63; 1962.

Gee, C. K. Estimating economic impacts of adjustments on Federal lands and estimating Federal rangeland forage values. Tech. Bull. 143. Fort Collins, CO: Colorado State University Experiment Station; 1981. 11 p.

Gee, C. K. The use of linear programming to estimate range forage values. In: Wagstaff, F. J., compiler. Proceedings—range economics symposium and workshop; 1982 August 31-September 2; Salt Lake City, UT. Gen. Tech. Rep. INT-149. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983: 89-92.

Nielsen, D. B.; Wennergren, E. Boyd. Public policy and grazing fees on Federal lands: some unresolved issues. Land and Water Law Review. 5(2): 293-320; 1970.

Nielsen, D. B. Economic duplication of variable versus single grazing fees. Journal of Range Management. 25: 2-7; 1972.

Pope, C. A., III; Wagstaff, Fred J. An economic evaluation of the Oak Creek Management Area, Utah. Gen. Tech. Rep. INT-224. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station; 1987. 14 p.

Roberts, N. K. Economic foundation for grazing use fees on public lands. Journal of Farm Economics. 455: 721-731; 1963.

Roberts, N. K. Discovering grazing values. Journal of Range Management. 20(6): 369-375; 1967.

Smith, A. D.; Beale, D. M. Pronghorn antelope in Utah: some research and observations. Publication 80-13. Salt Lake City, UT: Utah Division of Wildlife Resources; 1980. 88 p.

Sutton, W. L. History of Forest Service grazing fees. Journal of Range Management. 6(6): 393-398; 1983.

U.S. Department of Agriculture, Forest Service. Range project effectiveness analysis procedures. Handbook 2209.11. Washington, DC: U.S. Department of Agriculture, Forest Service; 1982. 82 p.

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management. 1985 grazing fee review and evaluation. Washington, DC: U.S. Department of Agriculture, Forest Service; 1985. 99 p.

Vass, A. F. Values of range grazing lands. Denver, CO: American Cattle Producers; 1940. 3 p.

Wagstaff, F. J. Evaluating proposed improvements of public rangeland. Gen. Tech. Rep. INT-150. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1983. 4 p.

Watson, R. S.; Holman, M. A. Price theory and its use. 4th ed. Boston: Houghton Mifflin Company; 1977. 445 p.

Wagstaff, Fred J.; Pope, C. Arden, III. 1987. Finding the appropriate forage value for analyzing the feasibility of public range improvements. Res. Pap. INT-378. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 4 p.

Eight methods for estimating the value of an animal unit month of public rangeland grazing generated estimates applicable to the Oak Creek area of central Utah. Of the eight estimates, six bracketed the range of acceptable estimates. The price paid for leasing similar rangeland was considered the most accurate estimate.

KEYWORDS: forage value, AUM value, public grazing value

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

U.S. GOVERNMENT PRINTING OFFICE: 1987-773-039/41044

United States
Department of
Agriculture

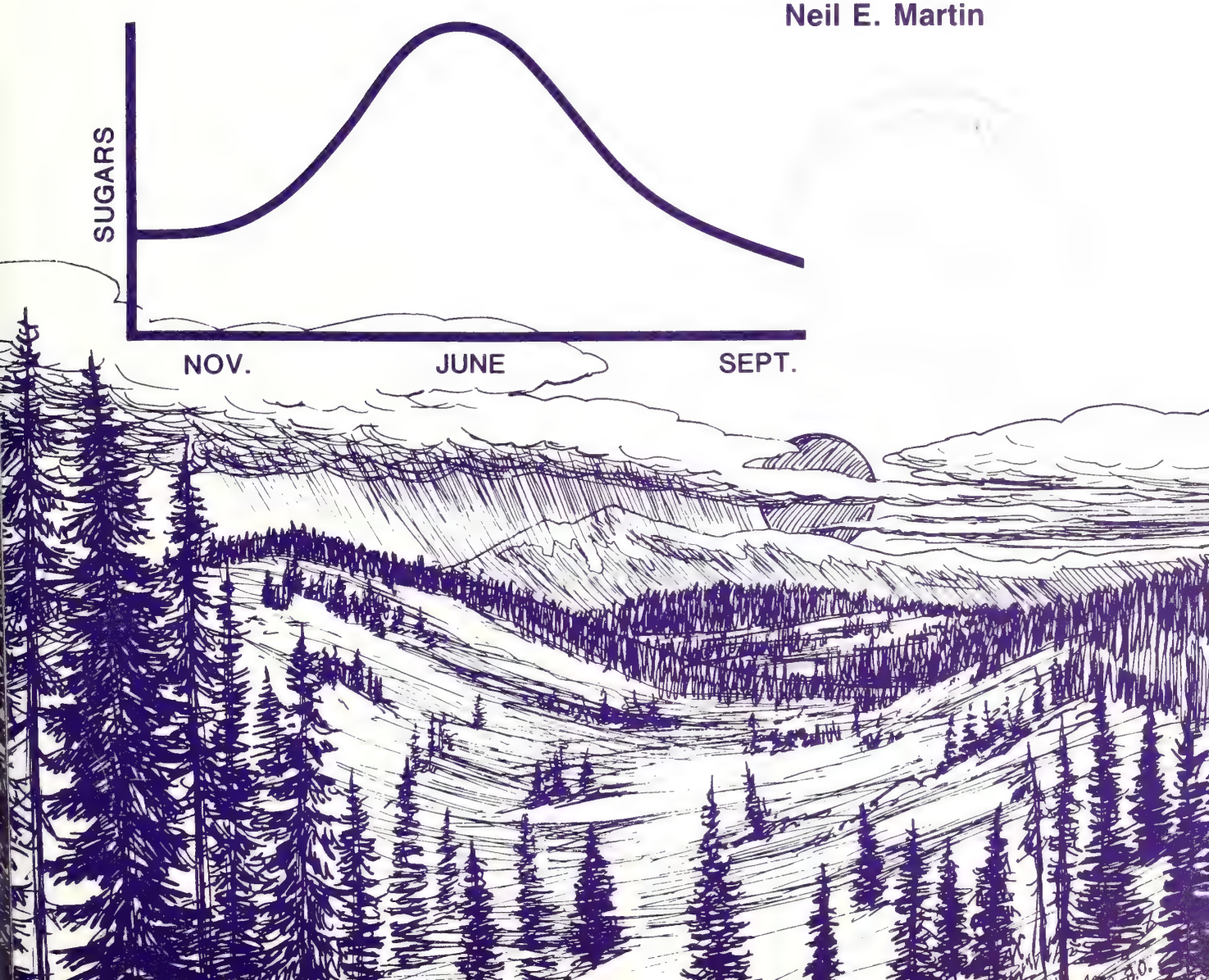
Forest Service

**Intermountain
Research Station**

Research Paper
INT-379

Soluble Sugar Concentrations in Needles and Bark of Western White Pine in Response to Season and Blister Rust

Neil E. Martin



THE AUTHOR

NEIL E. MARTIN is a research plant pathologist at the Intermountain Research Station's Forestry Sciences Laboratory in Moscow, ID. He has researched the physiology of blister rust, damage due to dwarf mistletoe in various habitats, and the biology of root-rot-causing fungi on western conifers. Current research emphasizes ecology, pathogenicity, and fruiting of *Armillaria* species.

RESEARCH SUMMARY

Amounts of soluble sugars in certain tissues of 12- to 16-year-old western white pine (*Pinus monticola* Dougl.) trees, each with a blister rust canker girdling about 50 percent of the bole circumference, were compared with rust-free trees. Fructose, glucose, sucrose, raffinose, and stachyose extracted from needles and healthy and diseased bark were identified with thin-layer chromatography and quantified with a densitometer. The host's seasonal growth cycle induced changes in sugar concentrations in current, 1-, and 2-year needles, but the bole cankers did not. Amounts of bark sugars characterized the activities of the rust fungus (*Cronartium ribicola* J.C. Fisch.) as well as the fall, winter, and summer seasons. The amounts of sugars in the bark decreased toward the cankers' centers except for raffinose and stachyose. The greatest differences in amounts of sugars in rusted and nonrusted bark tissues were found in February.

July 1987

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Soluble Sugar Concentrations in Needles and Bark of Western White Pine in Response to Season and Blister Rust

Neil E. Martin

INTRODUCTION

Qualitative and quantitative changes in soluble carbohydrates within conifer tissues occur throughout the year (Kozlowski and Keller 1966; Little 1970; Parker 1959; Zimmerman 1974). These changes are especially evident as responses to seasonal use and synthesis. Usually, monosaccharides and disaccharides predominate in needles and bark during the spring. As the flush of growth ceases and the newly expanded organs gain in net photosynthates, simple sugars are converted into oligosaccharides, illustrated in increases in raffinose and stachyose. Oligosaccharides characterize dormant conifer tissues. They do not remain indefinitely as storage molecules but are metabolized when ambient temperatures induce rapid growth the following spring.

Pathogens influence the metabolism of their host's tissues. This phenomenon has been studied extensively in many annual plant-obligate pathogen interactions and is known to include changes in respiration rates, photosynthesis rates, and qualitative and quantitative changes in metabolite pools (Brown 1936; Durbin 1967; Goodman and others 1967; Martin 1972; Schoeneweiss 1975; Siddiqui and Manners 1971; Welch and Martin 1975). Conversely, the metabolic or nutritional status of the host is known to influence the performance of some of its pathogens (Grainger 1956; Huber and Watson 1974; Schoeneweiss 1975). Changes in host physiology, such as those accompanying maturation or induced by climatic stimuli, may favor disease development (Allen 1966; Horsfall and Dimond 1957). In addition, the physiology of specific morphogenesis in the host appears necessary for, or is at least coincidental with, fungus morphogenesis. Chilling for 90 days at 2 °C satisfies the dormancy requirements and induces bud elongation in the white pine host; however, aecia production of *Cronartium ribicola* J.C. Fisch. commences only after, but not during, host dormancy (Wicker and Harvey 1969).

Because the soluble carbohydrate content of host conifers in the temperate zone reflects seasonal host physiology and because these sugars are also used by the obligatory blister rust fungus, it seemed that soluble sugar levels would be a sensitive measure of host and parasite demands. The objective of this research was to measure the effects of *C. ribicola* J.C. Fisch. and of seasons on the amounts of certain soluble sugars in the needles and in the bark of *Pinus monticola* Dougl.

MATERIALS AND METHODS

We selected 40 trees in a second-growth stand of 14- to 16-year-old western white pine growing on western white pine site 90 in an *Abies grandis/Pachistima myrsinites* habitat type (Daubenmire and Daubenmire 1968). This stand is 72 km east of Moscow, ID, in the Badger Meadows area of the East Fork of Potlatch Creek. We selected 20 trees with rust-infected stems and 20 with uninfected stems for uniformity in growth, size, habitat, and competition. Each infected tree had a canker in the lower half of the main stem that girdled 30 to 50 percent of the stem circumference. To alleviate the effects of branch infections on needle analysis, all branch cankers were removed 2 months before the first sampling and whenever additional infections became visible thereafter.

Each season, two or four cankered and canker-free trees were harvested for bark and needle samples. Bark was sampled at four locations on the diseased trees (Welch and Martin 1974): (1) sporulating areas: areas of blister rust cankers where pycnia and aecia are currently produced, (2) yellow margins: yellow canker boundary, (3) proximal: green bark proximal to the cankers but at least 1 cm away from the yellow margin, and (4) distal: green bark distal to a canker (always in the next higher growth segment to that of the canker). Bark was also sampled at two comparable bole locations on healthy trees. Although four diseased trees were individually sampled for needles in the field, the pulverized and freeze-dried samples of two trees had to be pooled to provide approximately 1 gram of freeze-dried tissue for analysis.

Three age classes of needles were sampled at random within each tree. Current-year, 1-year-old, and 2-year-old needles were sampled randomly from throughout the live crowns without regard to location of the bole canker. Three-year-old needles became senescent in June and were not sampled.

All samples were collected, quick-frozen on dry ice, and taken the same day to the laboratory where they were processed. Soxhlet extraction of all samples, clarification,

thin-layer chromatography (TLC) of all extracts, and densitometric quantification of isolated sugars followed the methods described by Martin and Welch (1975) and Welch and Martin (1972).

Data from the needles were analyzed as a balanced factorial design using standard biometric techniques. Bark sugar data required the following model for an unbalanced factorial analysis (Snedecor 1956):

$$Y_{ijk} = \mu + C_i + S_j + CS_{ij} + T_{k(i)} + \varepsilon_{ijk}$$

where

Y_{ijk} = dependent variables
μ = mean
C_i = grouping of disease class and of bark samples (C_1 = diseased versus nondiseased; C_2 = bark samples, 1 to 4 locations)
S_j = seasons
CS_{ij} = interaction between seasons and disease and bark
$T_{k(i)}$ = trees.

RESULTS

Sugar concentrations in needles of cankered and canker-free trees were indicative of the influence of seasons and of physiologic age (table 1). With the exception of sucrose, sugar levels, when considered collectively for all needles, showed a response to season through highly significant differences ($p = 0.05$) in the season means. Sucrose showed no statistically significant differences and less than half the variation found in the other sugars. Amounts of sugars within the November, February, and September collections decreased in the order fructose>glucose>sucrose>raffinose>stachyose. However, in the June collections, amounts of fructose were found to be similar or slightly greater than those of glucose. The seasonal patterns of amounts of fructose, glucose, and sucrose in all age classes of needles were similar, with the greatest amounts available in the needles sampled in the periods of slow tree growth (fall and winter) and the least amounts at the end of the accelerated growth period (June).

Table 1—Average concentrations of sugars in needles of blister rust-diseased and rust-free western white pines at four times during a growing season

Tree status	Needle age	Sugar (mg/g dry tissue)[1]				
		Fructose	Glucose	Sucrose	Raffinose	Stachyose
			November			
Diseased trees	Current	17.4	16.2	11.6	7.0	0.0
	1 year	16.8	14.8	13.6	8.1	0.0
	2 years	16.8	14.5	11.7	7.1	0.0
Rust-free trees	Current	16.2	15.0	13.3	7.5	0.0
	1 year	15.3	14.4	13.2	7.5	0.0
	2 years	15.5	13.5	13.8	6.6	0.0
			February			
Diseased trees	Current	13.4	11.7	12.5	11.3	3.2
	1 year	14.7	12.1	9.9	10.6	2.9
	2 years	16.0	14.5	9.5	9.9	3.0
Rust-free trees	Current	14.7	13.4	12.4	10.9	3.2
	1 year	16.0	13.9	8.8	9.8	2.7
	2 years	15.6	13.8	10.9	7.8	2.7
			June			
Diseased trees	Current	12.2	13.0	11.0	Trace[2]	0.0
	1 year	10.6	11.9	12.1	Trace	0.0
	2 years	11.1	11.1	9.9	Trace	0.0
Rust-free trees	Current	13.4	13.2	8.2	Trace	0.0
	1 year	11.8	12.0	11.6	Trace	0.0
	2 years	10.2	10.3	13.3	Trace	0.0
			September			
Diseased trees	Current	17.4	16.6	10.6	3.8	0.0
	1 year	17.8	16.5	10.1	Trace	0.0
	2 years	18.2	16.3	10.3	Trace	0.0
Rust-free trees	Current	16.9	18.1	10.3	Trace	0.0
	1 year	19.8	17.2	9.6	Trace	0.0
	2 years	19.5	17.0	10.9	Trace	0.0

[1]Average of four trees, each tree quantified by eight replicate TLC analyses of each sample (Welch and Martin 1972).

[2]The minimum threshold for accurate measurement was found to be approximately 3 mg.

The effect of physiologic age of needles is best illustrated by comparisons of the amounts of raffinose. All age classes had trace amounts (approximately 3 mg/g) in June and September. However, as needles age they apparently lose the capacity for certain oligosaccharide storage as indicated by the amounts of raffinose in the current needles decreasing to lesser amounts in 1-year-old and 2-year-old needles. Stachyose, another oligosaccharide, was also detected only in the February collections in all needle-age classes (3.0 mg/g, range 2.7 to 3.2), but the influence of needle age on amount of stachyose accumulated was not evident. Comparisons of blister-rust-diseased and disease-free trees showed no differences in these sugars between seasons or classes of needles.

All distal bark sampled in February and June had sugar amounts decreasing in the order sucrose>fructose>glucose >raffinose>stachyose (table 2). Only comparisons of glucose in the distal bark of rust-diseased and rust-free trees in the February (11.7 mg/g vs. 14.1 mg/g) and September (12.2 mg/g vs. 14.9 mg/g) collections showed significant differences. Concentrations of sucrose, raffinose, and stachyose in bark showed the following seasonal changes: sucrose occurred in the largest amounts in June (19.9 mg/g), then amounts receded through September to the smallest amounts in November (14.4 mg/g), then in increasing amounts through February (16.6 mg/g) to June. Raffinose and stachyose concentrations in the distal samples of diseased and rust-free trees responded to seasons differently from sucrose. Their peak concentrations were in the November (12.5 mg/g, 8.4 mg/g) and February (9.4 mg/g, 10.2 mg/g) collections, and their lowest concentrations in the June (3.5 mg/g, 0.0 mg/g) and September (4.6 mg/g, 0.0 mg/g) collections.

Proximal bark also contained all sugars in the same relative amounts as were found in the distal bark. Proximal bark sampled from trees affected and unaffected by the rust had similar amounts of each sugar (table 2). Sucrose levels had a higher concentration for February (12.1 mg/g) and a lower range of concentrations in proximal bark in healthy than in rust-affected trees; the differences were significant ($p = 0.05$). Proximal bark from both kinds of trees repeated the seasonal effects found in

Table 2—Concentrations of sugars in bark tissues of blister rust-diseased and rust-free western white pines at four times during a growing season

Tree status	Location of bark sample in relation to canker[1]	Sugar (mg/g dry tissue)[2]				
		Fructose	Glucose	Sucrose	Raffinose	Stachyose
		November				
Diseased trees	Distal	15.0	12.8	14.4	12.5	8.4
	Proximal	11.0	7.9	11.7	10.8	7.7
	Yellow margin	9.2	5.9	9.1	10.8	7.7
	Sporulating area	10.2	11.8	14.0	10.6	8.8
Rust-free trees	Distal[3]	—	—	—	—	—
	Proximal[3]	—	—	—	—	—
		February				
Diseased trees	Distal	14.0	11.7	16.6	9.4	10.2
	Proximal	16.8	12.9	12.1	6.8	6.5
	Yellow margin	14.4	12.7	12.1	8.2	6.0
	Sporulating area	3.1	3.3	4.8	3.6	5.2
Rust-free trees	Distal	14.3	14.1	16.1	9.2	8.6
	Proximal	16.6	11.4	16.9	9.8	8.7
		June				
Diseased trees	Distal	15.5	13.3	19.9	3.5	0.0
	Proximal	14.6	12.7	18.9	2.9	0.0
	Yellow margin	11.3	9.9	15.7	3.2	0.0
	Sporulating area	10.3	9.7	16.8	3.1	0.0
Rust-free trees	Distal	16.9	14.3	18.0	3.4	0.0
	Proximal	11.6	10.4	16.0	3.1	0.0
		September				
Diseased trees	Distal	15.7	12.2	15.5	4.6	0.0
	Proximal	14.3	12.7	15.0	5.3	0.0
	Yellow margin	15.4	14.1	13.5	5.2	[4]1.9
	Sporulating area	12.0	10.6	11.7	4.7	4.0
Rust-free trees	Distal	17.7	14.9	12.9	5.2	0.0
	Proximal	16.6	13.6	13.8	4.0	0.0

[1]Distal = green bark in the next high growth segment to that of the blister rust canker; Proximal = green bark 1 cm away from the canker's yellow margin; Yellow margin = yellow bark at the leading boundary of the blister rust canker; Sporulating area = areas within the blister rust canker where pycnia and aecia are produced.

[2]Each sample quantified by eight replicated TLC analyses (Welch and Martin 1972).

[3]These tissues were not available for analysis.

[4]The minimum threshold for accurate measurement was found to be approximately 3 mg.

distal barks. For example, no seasonal trends were noted in amounts of fructose and glucose. Again, sucrose peaked in the June collection of proximal bark of cankered trees (18.9 mg/g) and showed the least amount in November (11.7 mg/g). Raffinose and stachyose were at their greatest concentrations in November (10.8 mg/g, 7.7 mg/g) and February (6.8 mg/g, 6.5 mg/g), with lesser amounts in June (2.9 mg/g, 0.0 mg/g) and September (4.0 mg/g, 0.0 mg/g).

Yellow margin bark (the yellowed bark that identifies the advancing margin of the blister rust canker) had significantly less fructose, glucose, and sucrose than either distal or proximal bark locations, but had similar levels of raffinose and stachyose (table 2). Seasonally associated trends in amounts of all sugars were found although patterns among seasons differed (table 2). Fructose and glucose were seasonally cyclic with alternating highs and lows. For example, fructose concentrations were low in November (9.2 mg/g), high in February (14.4 mg/g), lower in June (11.3 mg/g), and higher in September (15.4 mg/g). Seasonal values of sucrose concentrations were greatest in June (15.7 mg/g) and smallest in November (9.1 mg/g). Raffinose and stachyose were found in characteristically greater amounts in November (10.8 mg/g, 7.7 mg/g) and February (8.2 mg/g, 6.0 mg/g) rather than in June (3.2 mg/g, 0.0 mg/g) and September (5.2 mg/g, 1.9 mg/g). Contrary to the decreases shown by distal and proximal samples, raffinose and stachyose each showed a slight increase in September (5.2 mg/g, 1.9 mg/g) from the June low (3.2 mg/g, 0.0 mg/g).

The areas of the blister rust canker in which sporulation of the rust fungus occurs generally had smaller concentrations of each sugar than did other bark locations, and had a seasonal pattern unlike that of other bark samples. Table 2 illustrates that fructose and glucose concentrations were relatively similar in November (10.2, 11.8), June (10.3, 9.7), and September (12.0, 10.6) collections and at least three times the amounts (3.1 to 3.3) found in the February collections. Sucrose levels were consistent with those found in the other areas, except that the February (4.8) rather than November (14.0) samples contained the least amount. Amounts of raffinose in the sporulating areas deviated from the patterns found in the yellow margin samples, but stachyose showed no deviation. Concentrations of raffinose were consistently high in the November samples (10.6) but were depressed to lows similar to those for stachyose in the February (3.6), June (3.1), and September (4.7) collections.

DISCUSSION

The four sampling periods—November of one year, and February, June, and September of the following year—were chosen to show that an obligate organism, the rust, is at times physiologically out of phase with its perennial host, the pine. For example, in our part of the temperate zone, the Northern Rocky Mountains, western white pine becomes dormant between September and November and its growth has noticeably slowed or stopped. However, blister rust growth such as canker enlargement and yellowing of the bark continue at a rate responsive to bark temperatures. That is, the rate decreases as temperatures decline and increases as bark temperatures increase. As early as February, the 14-week to 16-week cold temperature requirements for resumption of growth after dormancy of western white pine have been fulfilled (Steinhoff and Hoff 1972). Ambient temperatures of −12 to 2 °C continue host dormancy, but cankers enlarge whenever insolation increases bark temperatures to a level suitable for the blister rust fungus to grow.

April and May sampling periods were avoided because both organisms are metabolically very active at that time as evidenced in rapid changes in morphology—for example, current-year needle expansion, rapid leader growth, rapid canker enlargement, profuse aeciospore liberation, and pycniosori activity. These evident and dramatic changes are probably accompanied by rapid turnover within metabolic reservoirs of soluble sugars. By June, except for some canker enlargement, these activities have subsided and a balanced but dynamic equilibrium in sugar metabolism is likely reached between host and parasite.

Western white pines retain three generations of needles during any year. Researchers have found quantitative differences in starch, sugars, and nitrogen compounds between each generation of needles (Kozlowski and Keller 1966). In the research reported here, sampling was timed to minimize differences in amounts of soluble sugars brought about by the demands of host growth as well as the impact of immature or senescent needles. For example, although current-year needles were sampled twice in the year in which they were formed (June and September), both sampling dates were after the needles were fully expanded and are no longer juvenile but are considered as physiologically mature as 2- and 3-year-old needles. Needles in their third growing season and sampled in February of the following year are of comparable physiological maturity because they have remained green and free of the evidence of senescence that will appear later in April and May. These needles were not sampled in June because the 3-year-old needles, now in their fourth growing season, were yellow to brown, indicating a probable bias in the analysis due to senescence and death effects.

Sugar concentrations in all needle age classes responded to growth activities of the host. Concentrations of sugars were greater during dormancy than active growth. Fructose and glucose concentrations, because of their direct involvement in catabolic as well as anabolic metabolism, were found to coincide closely with the demands of tree growth. Raffinose and stachyose were noticeable only as storage molecules in that they were measurable in dormant periods and undetectable in periods of active growth. In contrast, sucrose, a highly translocatable molecule, was found in similar concentrations in all samples. This suggests that, through translocation, pools of sucrose can have high turnover rates but be maintained at similar levels and therefore appear to be insensitive to host physiological activities.

Amounts of sugars in needles of these western white pines with bole cankers do not characterize the cankered trees nor distinguish them from healthy trees. Intuitively, stem infections could jeopardize the health of foliage as evidenced in diseases of many cultivated annuals, a phenomenon upon which aerial surveys rely. However,

such is not the case in the perennial hosts having a perennial infection disproportionately small when compared to the biomass of the host. But as the blister rust cankers approach complete girdling of the stems (80 to 100 percent of the circumference), death of the portions above the cankers is evident; needle colors change from green to yellow to reddish brown. Before their rapid decline, however, all needles are of normal color and apparently are capable of near normal metabolism as is indicated by sugar concentrations found comparable to those in needles of healthy trees.

The impact by blister rust to soluble sugar pools in pine bark was measurable in June (Welch and Martin 1975). However, there were no apparent differences between seasons in amounts of fructose, glucose, and sucrose in bark located distally from the cankers compared to similarly located bark of noncankered trees. Infection depressed the canker levels of fructose and glucose without significantly altering sucrose levels. Although some differences are not significant, the implications within the data are that infections have an area of influence extending a limited distance beyond canker margins but does not include the foliage. These findings help explain the absence of an impact by the rust upon host growth (Buchanan 1938) until girdling of the bole is complete. That this disease affects only locally the amounts of certain sugars in certain tissues is also evident in the raffinose and stachyose concentrations. The seasonal concentrations of these sugars were unaffected by the presence of blister rust in another location on the bole. Regardless of blister rust, bark, like needles, showed sugar concentrations were highest during host dormancy and lowest during rapid growth.

Sugar concentrations in proximally located bark exhibited the same trends for each sugar as those found in the distal bark samples. Samples of proximal bark had smaller amounts of fructose, glucose, and sucrose, but similar amounts of raffinose and stachyose to those found in distal bark. The distal and proximal bark, although separated physically, are physiologically similar in their storage capacities for sugars as is evidenced in the similarity of raffinose and stachyose concentrations. Because the rust fungus is making its initial invasion into these tissues (Ehrlich and Opie 1940), the implications are that the lesser amounts of fructose, glucose, and sucrose are due to the metabolic demands of the neighboring, greater concentration of the fungus in the yellow margin.

Bark tissues inhabited by the blister rust fungus—the yellow margin of the cankers and the sporulating areas—exhibited the same trends in sugar concentrations that characterized the proximal bark locations. As the sample locations progressed toward the canker centers, amounts of soluble fructose and glucose were less. This may show that small pools of these sugars reflect diminished needs after sporulation or that glucose has been synthesized into chitin, the glucosamine constituent of the fungal cell wall, a compound known to be present in this rust (Martin 1967).

The notable contrast in the low February levels of fructose, glucose, and sucrose in sporulating areas when compared to relative levels of the same sugars in other bark tissues in February also indicates that metabolism on the part of the blister rust fungus is greater than that of the pine tissues. Apparently, soluble sugars are being assimilated into aeciospores, which are subsequently dispersed from April through early June. Synthesis of pycnial fluid, which contains a high proportion of sugar alcohols and fructose (Wicker and others 1976), and synthesis of sugar alcohols in rust invaded bark (Welch and Martin 1975) would also utilize fructose at a time when host reserves in raffinose and stachyose are not available for maintaining a constant reservoir. Deductively, February is a period of late dormancy in the host and early spore development in the fungus in which the metabolism of pathogen and host are not synchronized in their rates of use of common pools of metabolites. This period may be a point in the life cycle of the pathogen at which it could be vulnerable to chemical attack while the host remains insensitive. This would achieve target selectivity in chemical control and minimize ecological impacts (Sbragia 1975).

REFERENCES

Allen, P. J. 1966. The role of the host in the development of disease symptoms—a review. Phytopathology. 56(3): 255-260.

Brown, W. 1936. The physiology of host/parasite relations. Botanical Review. 2: 236-281.

Buchanan, T. S. 1938. Blister rust damage to merchantable western white pine. Journal of Forestry. 36: 321-328.

Daubenmire, R.; Daubenmire, J. B. 1968. Forest vegetation of eastern Washington and northern Idaho. Tech. Bull. 60. Pullman, WA: Washington State University, Washington Agricultural Experiment Station, College of Agriculture. 104 p.

Durbin, R. D. 1967. Obligate parasites: effect on the movement of solutes and water. In: Mirocha, C. J.; Uritani, I., eds. The dynamic role of molecular constituents in plant-parasite interaction. St. Paul, MN: American Phytopathological Society: 80-99.

Ehrlich, J.; Opie, R. L. 1940. Mycelial extent beyond blister rust cankers on *Pinus monticola*. Phytopathology. 30: 611-620.

Goodman, R. N.; Kiraly, Z.; Zaitlin, M. Vascular transport. 1967. In: The biochemistry and physiology of infectious plant disease. Princeton, NJ: D. Van Nostrand Co.: 281-307.

Grainger, J. 1956. Host nutrition and attack by fungal parasites. Phytopathology. 46: 445-456.

Horsfall, J. G.; Dimond, A. E. 1957. Interactions of tissue sugar, growth substances, and disease susceptiblity. Z. Pflanzenkr. Pflanzenpathol. Pflanzenschutz. 64: 415-421.

Huber, D. M.; Watson, R. D. 1974. Nitrogen form and plant disease. Annual Review of Phytopathology. 12: 139-165.

Kozlowski, T. T.; Keller, T. 1966. Food relations of woody plants. Botanical Review. 32: 293-382.

Little, C. H. A. 1970. Seasonal changes in carbohydrate and moisture content in needles of balsam fir (*Abies balsamea*). Canadian Journal of Botany. 48(1): 2021-2028.

Martin, N. E. 1967. Histochemical analysis of the blister rust fungus, *Cronartium ribicola*. Phytopathology. 57: 820-821. Abstract.

Martin, N. E. 1972. Influence of blister rust on inorganic solute concentrations in western white pine. Phytopathology. 62(2): 226-229.

Martin, N. E.; Welch, B. J. 1975. Single dimension, multiple development thin-layer chromatography of sugars for densitometric quantification. Res. Note INT-192. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 7 p.

Parker, J. 1959. Seasonal changes in white pine leaves: a comparison of cold resistance and free-sugar fluctuations. Botanical Gazette. 121: 46-50.

Sbragia, R. J. 1975. Chemical control of plant diseases: an exciting future. Annual Review of Phytopathology. 13: 257-269.

Schoeneweiss, D. F. 1975. Predisposition, stress, and plant disease. Annual Review of Phytopathology. 133: 193-211.

Siddiqui, M. Q.; Manners, J. G. 1971. Some effects of general yellow rust (*Puccinia striiformis*) infection on 14-carbon assimilation, translocation, and growth in a spring wheat. Journal of Experimental Botany. 22(73): 792-799.

Snedecor, G. W. 1956. Statistical methods. Ames, IA: Iowa State University Press. 534 p.

Steinhoff, R. J.; Hoff, R. J. 1972. Chilling requirements for breaking dormancy of western white pine seedlings. Res. Note INT-153. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 6 p.

Welch, B. L.; Martin, N. E. 1972. Quantitative analysis of sugars by densitometric inspection of thin-layer chromatograms: analysis of method. Journal of Chromatography. 72: 395-364.

Welch, B. L.; Martin, N. E. 1974. Evidence of pectinase activity between *Cronartium ribicola* and *Pinus monticola*. Phytopathology. 64: 1287-1289.

Welch, B. L.; Martin, N. E. 1975. Effects of *Cronartium ribicola* on soluble sugars in *Pinus monticola* bark. Phytopathology. 65: 1025-1026.

Wicker, E. F.; Harvey, A. E. 1969. Dormancy and aecia production by *Cronartium ribicola*. Phytopathology. 59: 1057. Abstract.

Wicker, E. F.; Mosher, D. P.; Wells, J. M. 1976. Organic constituents of *Cronartium ribicola* pycnial fluid. Phytopathologische Zeitschrift. 87: 97-106.

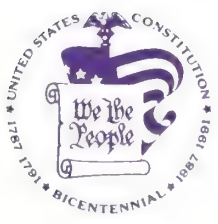
Zimmerman, M. H. 1974. Storage, mobilization, and circulation of assimilates. In: Zimmerman, M. H.; Brown, C. L., eds. Trees: structure and function. New York: Springer-Verlag: 307-324.

Martin, Neil E. 1987. Soluble sugar concentrations in needles and bark of western white pine in response to season and blister rust. Res. Pap. INT-379. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 6 p.

Amounts of soluble sugars in certain tissues of 12- to 16-year-old western white pine (*Pinus monticola*) trees with blister rust cankers were compared with rust-free trees. The host's seasonal growth cycle induced changes in sugar concentrations in current, 1-, and 2-year needles, but the bole cankers did not. Amounts of bark sugars characterized the activities of the rust fungus (*Cronartium ribicola*) as well as the fall, winter, and summer seasons. The greatest differences in amounts of sugars in rusted and nonrusted bark tissues were found in February.

KEYWORDS: host-parasite physiology, *Cronartium ribicola*, *Pinus monticola*, soluble carbohydrates, disease influences, host responses, forest tree pathology

---



USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

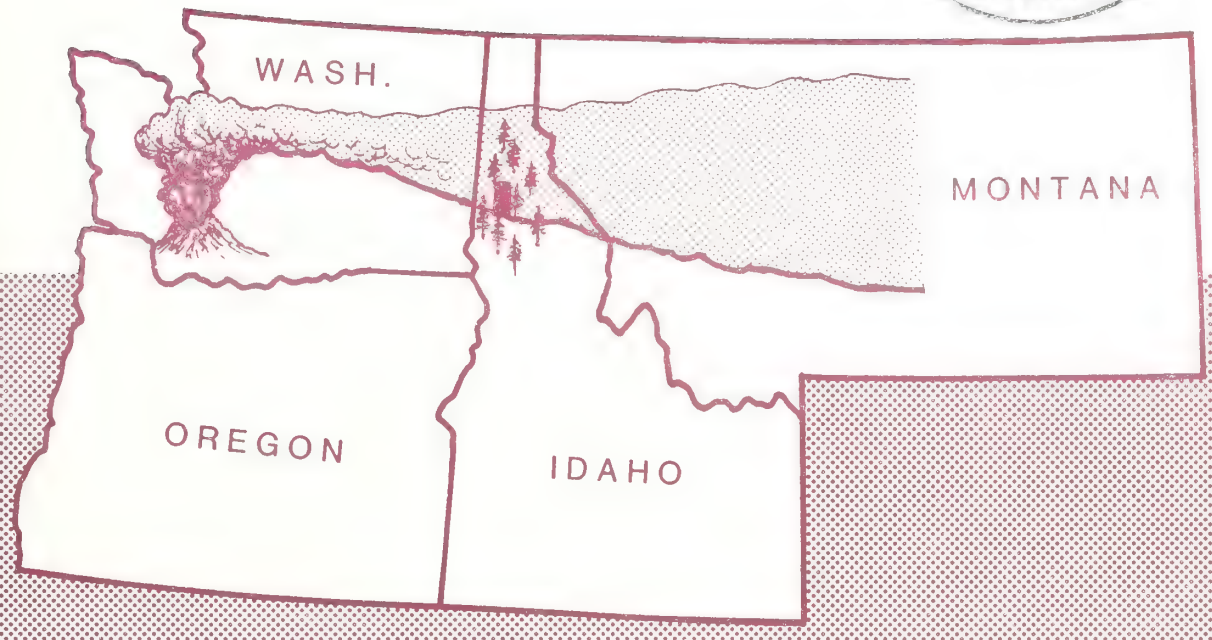
**Intermountain
Research Station**

Research Paper
INT-380

Effects of Persistent Volcanic Ash on Douglas-fir in Northern Idaho

David E. Bilderback
Clinton E. Carlson

FEB 15 1983



THE AUTHORS

DAVID E. BILDERBACK is professor and chairman, Department of Botany, University of Montana, Missoula. He was awarded his B.S. in biology in 1961 and Ph.D. in biology in 1968 from the University of Oregon. He was an N.I.H. Postdoctoral Fellow at the Plant Research Laboratory at Michigan State University in 1970 and joined the faculty of the Department of Botany at the University of Montana in 1972. His research interests are plant growth and development, and the effects of air pollution on vegetation.

CLINTON E. CARLSON is a research forester at the Intermountain Research Station, Forestry Sciences Laboratory, Missoula, MT. He has conducted extensive work on the effects of air pollution on forest ecosystems and currently is studying interactions of western spruce budworm and Northern Rocky Mountain forests. He holds B.S. and M.S. degrees in forestry and a Ph.D. in botany from the University of Montana.

RESEARCH SUMMARY

The eruption of Mount St. Helens on May 18, 1980, deposited tephra (volcanic ash) on forests of northern Idaho. Tephra persisted on foliage of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), with 12.8 to 15.7 mg ash/gram tissue dry weight remaining on 1979 and 1980 needles 16 months after the eruption. Although total chlorophyll was reduced and chlorosis occurred in needles from affected stands, the persisting tephra did not significantly influence tree growth—the number of needles per stem segment, their dry weight, and radial stem increment were unaffected. We conclude that ashfall had a slight but only temporary effect on Douglas-fir in northern Idaho.

August 1987
Intermountain Research Station
324 25th Street
Ogden, UT 84401

Effects of Persistent Volcanic Ash on Douglas-fir in Northern Idaho

David E. Bilderback
Clinton E. Carlson

INTRODUCTION

The eruption of Mount St. Helens on May 18, 1980, deposited about 1.5 to 2.0 km^3 of tephra (volcanic ash) on farm, range, and forest lands of eastern Washington, northern Idaho, and western Montana (Hammond 1980). The explosion destroyed coniferous forests near the volcano. To the east, acaulescent and prostrate vegetation was damaged by ash loading (Mack 1981), and agricultural crop losses were estimated at $100 million (Cook and others 1981). Ash accumulation on apple leaves reduced photosynthetic rates by nearly 25 percent and increased photorespiration (Kennedy 1981). Near the volcano, needles of Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) were damaged by persistent ash (Seymour and others 1983). Chlorosis occurred within 3 weeks of the eruption and was attributed to high foliar temperatures induced by tephra on the needles. Seymour and others (1983) concluded the ash probably altered the surface characteristics of the needles, allowing larger solar heat flux. Hinckley and others (1984) found that ash deposition near the blast zone reduced height and diameter growth of both Pacific silver fir and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and reduced 1980 ring width of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco). Removal of tephra from needles of Pacific silver fir and noble fir (*Abies procera* Rehd.) increased subsequent height growth (Zobel and Antos 1985).

In the fall of 1980, needles of Douglas-fir growing in northern Idaho, 480 km from the volcano, retained 420 mg of tephra per gram needle dry weight, but needles of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) were free of ash (Bilderback and Slone 1986). This study was conducted to determine if persistent ash deposits affected chlorophyll content and growth of the Douglas-fir. Ponderosa pine was not studied because tephra was not persistent on its foliage.

METHODS

Two stands of trees, one tephra-coated and the other unaffected, were selected for comparison. The stand with tephra-coated foliage was 27.2 km south of Coeur d'Alene, ID, about 480 km northeast of the volcano. This site received about 1 cm of tephra. The control stand was located 11.2 km northeast of Coeur d'Alene, nearly out of the plume path. It received less than 0.01 cm of tephra. Both locations were at 658 km elevation, faced south, and had slopes varying from 0 to 40 percent. Habitat type, an indicator of site similarity (Pfister and others 1977), was *Pseudotsuga menziesii/Physocarpus malvaceous* at both locations.

The stands were similar in structure. The average diameters, measured 1.37 m above ground, were 41.4 cm and 45.5 cm for the tephra and control stands, respectively. The control stand was about 100 years old and the tephra stand about 85. The tephra stand was more dense, with 343 stems per hectare compared to 188 for the control.

In September 1981, 16 months following the eruption, six plots were installed 45 m apart along a randomly located transect in the control stand. Five plots were installed along each of two parallel, randomly located transects at the tephra stand. Within each control plot, two midcrown branches from opposing sides of five dominant/codominant Douglas-fir trees were clipped, placed in plastic bags, and transferred to a freezer for storage. At the tephra stand, six trees, similar in size to those selected in the control, were sampled at each plot. Thus, a total of 90 trees were sampled in the study. To determine the influence of ash on bole radial growth, two increment cores were taken 1.37 m above ground level, 90 degrees from each other around the bole of each sample tree.

To determine the amount of persistent tephra on the 1979 and 1980 foliage, 20 needles of each age class were randomly selected from each of the two collected branches of each tree and washed in a small volume of water. The suspension was filtered and tephra collected on preweighed Millipore filters. The filters and needles were ovendried and weighed to determine the amount of tephra (mg/gram needle dry weight) that was on the needles prior to washing.

For each tree sampled, all lateral branchlets bearing 1979, 1980, and 1981 needles were clipped from each sample branch. Branchlets were cut at the nodes, and internodes were segregated by date of origin—1979, 1980, and 1981. Thus, 270 segments were evaluated: 90 trees × 3 years/tree. All needles of three randomly selected internodes within each age class were counted and assessed for

chlorosis on a scale of 0 (no damage) to 4 (brown needles). Then they were stripped from the shoots and pooled.

To determine if persistent ash affected chlorophyll content, five needles were randomly selected from each age class, split lengthwise with a razor blade, pooled, and extracted with 95 percent methanol for 72 hours. A total of 270 extractions and analyses were done (90 trees × 3 ages/tree). Chlorophyll was determined by the method of Mackinney (1941).

Total chlorophyll was computed as:

$$Chl = 22.5 \times A_{650} + 4.0 \times A_{665}$$

where A is the absorbance at 650 and 665 nm.

To determine whether the tephra influenced radial stem growth, two growth ratios were computed for all sample trees:

1. $\frac{G_{1980}}{\bar{X}G_{(1970\text{-}1979)}}$ and 2. $\frac{G_{1980}}{G_{1979}}$

where G is the radial growth for a year or period, measured on the increment core.

Variables were compared between stands using standard t-test procedures (Sokal and Rohlf 1969).

RESULTS AND DISCUSSION

Five months after eruption of Mount St. Helens, needles of Douglas-fir in northern Idaho receiving about 1 cm of tephra were still heavily coated on both surfaces with 420 mg of tephra per gram needle dry weight (Bilderback and Slone 1986). The tephra had not been dislodged from the needles even though the region received 17.5 cm to 24.3 cm of summer precipitation. The 1979 and 1980 fir needles at that site retained 15.7 and 12.8 mg of tephra per gram needle dry weight, respectively, 16 months after the eruption (table 1). In contrast, foliage from trees growing at the control site had only 15 mg of tephra per gram of needle dry weight 5 months after eruption (Bilderback and Slone 1986) and no ash thereafter (table 1). Samples from one tree in the tephra stand were lost, reducing the trees sampled from 90 to 89.

Total chlorophyll was significantly less ($P \leq 0.05$) in the 1979 and 1980 Douglas-fir needles from the tephra-laden stand (table 1). These needles also were chlorotic. A small but significant amount of chlorosis also occurred in 1981 needles from the ashed stand, even though these needles were never exposed directly to the tephra. Although the reason for chlorosis of new needles is not understood, it appeared to be related to ashfall.

Seymour and others (1983) investigated foliage damage to Pacific silver fir following ashfall. Persistent ash around the needles did not mechanically or chemically damage the cuticle of needles they studied or alter water potentials but significantly elevated needle temperature by 10 °C. Tephra deposition apparently altered foliage geometry, and the resulting change in the energy balance of the system caused needle temperatures to increase to lethal levels (Seymour and others 1983). In a similar manner, higher temperatures caused by a coating of tephra may have caused chlorosis and a decrease in total chlorophyll of Douglas-fir needles we sampled in northern Idaho.

In our study, volcanic ash deposition did not affect the number of needles on stem segments. Primordia of needles elongating in 1981 would have been initiated in buds during 1980 when the foliage was heavily laden with ash, but

Table 1—Comparisons of chlorophyll concentration and tree growth between the control and ashed stands

Variable	Year of needle elongation	Stand		Student's t value	Number of observations	Probability
		Control	Ashed			
Ash weight on needles (mg/g needle dry weight, 16 months after eruption)	1979	0	15.7	10.41	89	0
	1980	0	12.8	11.83	89	0
	1981	—	—	—	—	—
Total chlorophyll (mg/g needle dry weight)	1979	5.39	4.86	2.20	89	0.031
	1980	5.03	4.17	3.99	89	0
	1981	3.39	3.29	0.69	89	0.489
Chlorosis code	1979	0	1.71	15.08	89	0
	1980	0	1.94	16.44	89	0
	1981	0	0.47	4.75	89	0
Needles/stem segment	1979	71	67	1.06	89	0.290
	1980	54	57	0.98	89	0.329
	1981	71	70	0.51	89	0.609
Mean needle dry weight (g)	1979	0.0037	0.0042	2.17	89	0.033
	1980	0.0028	0.0034	3.30	89	0.001
	1981	0.0030	0.0035	1.77	89	0.080
Growth ratio A[1]	—	1.14	1.07	1.02	89	0.310
Growth ratio A[2]	—	1.03	1.01	0.21	89	0.837

[1]Ratio of 1980 radial increment to mean 1970-79 radial increment.
[2]Ratio of 1980 radial increment to 1979 radial increment.

no significant difference ($P \leq 0.05$) was found between the two stands for 1981, 1980, or 1979 needle counts.

Average dry weight of 1979 and 1980 needles (washed) from the stand that received ash was significantly greater than from the control stand. The 1979 needles grew prior to the ashfall. Because the difference in needle dry weight between age classes was about the same before and after ashfall, the difference cannot be attributed to the ash. Stand or site factors likely were responsible.

Hinckley and others (1984) found significant radial growth reduction of Pacific silver fir and western hemlock in an area with a 6- to 8-cm deposit of tephra. Douglas-fir at a site with 12 cm of tephra experienced a 9 to 31 percent reduction in the 1980 ring width compared to the 1979 ring width. Zobel and Antos (1985) found that tephra had little effect on annual Douglas-fir height growth at a site receiving 13 cm of tephra. In our study in northern Idaho, which received only about 1 cm of tephra, radial stem growth was not altered even though the ash persisted on the foliage. Neither the ratio of the 1980 to 1979 increment nor the ratio of the 1980 to 10-year mean increment (1970-79) was significantly different between stands (table 1).

In light of these data, we conclude that the 1980 ashfall from Mount St. Helens had little effect on Douglas-fir in northern Idaho, even though the tephra still persisted on the needles 16 months after the eruption. In spite of a small decrease in total chlorophyll and an increase in visible chlorosis, tree growth was unaffected as indexed by needles/shoot, needle dry weight, and radial stem growth. The eruption and associated ashfall were only a minor and temporary perturbation to Douglas-fir in northern Idaho.

REFERENCES

Bilderback, D. E.; Slone, J. H. 1986. The persistence of Mount St. Helens ash on conifer foliage. In: Bilderback, D. E., ed. Mount St. Helens 1980: the botanical consequences of the explosive eruptions. Los Angeles: University of California Press: 282-289.

Cook, R. J.; Barron, J. C.; Papendick, R. I.; Williams, G. J., III. 1981. Impact on agriculture of the Mount St. Helens eruptions. Science. 211: 16-22.

Hammond, P. E. 1980. Associated Engineering Geology Newsletter. 12: 15.

Hinckley, T. M.; Imoto, H.; Lee, K.; Lacker, S.; Morikawa, Y.; Vogt, K. A.; Grier, C. C.; Keyes, M. R.; Teskey, R. O.; Seymour, V. 1984. Impact of tephra deposition on growth in conifers: the year of the eruption. Canadian Journal of Forest Research. 14: 731-739.

Kennedy, R. A. 1981. The eruption of Mount St. Helens: impact on agriculture and the effects of Mount St. Helens ash on plants. Scanning Electron Microscopy. 4: 235-241.

Mack, R. N. 1981. Initial effects of ashfall from Mount St. Helens on vegetation in eastern Washington and adjacent Idaho. Science. 213: 537-539.

Mackinney, G. 1941. Absorption of light by chlorophyll solutions. Journal of Biological Chemistry. 140: 315-322.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 174 p.

Seymour, V. A.; Hinckley, T. M.; Morikawa, Y.; Franklin, J. F. 1983. Foliage damage in coniferous trees following volcanic ashfall from Mount St. Helens. Oecologia. 59: 339-343.

Sokal, R. R.; Rohlf, F. J. 1969. Biometry. San Francisco, CA: W. H. Freeman and Co. 776 p.

Zobel, D. B.; Antos, J. A. 1985. Response of conifer shoot elongation to tephra from Mount St. Helens. Forest Ecology and Management. 12: 83-91.

Bilderback, David E.; Carlson, Clinton E. 1987. Effects of persistent volcanic ash on Douglas-fir in northern Idaho. Res. Pap. INT-380. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 3 p.

The May 18, 1980, eruption of Mount St. Helens deposited volcanic ash on forests of northern Idaho. Ash persisted on foliage of Douglas-fir (*Pseudotsuga menziesii* var. *glauca*)—12.8 to 15.7 mg ash/gram tissue dry weight remained on 1979 and 1980 needles 16 months following the eruption. Ashfall reduced chlorophyll concentrations and caused needle chlorosis but did not significantly influence tree growth.

KEYWORDS: Mount St. Helens, ash, *Pseudotsuga menziesii*, tephra, forest biology

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

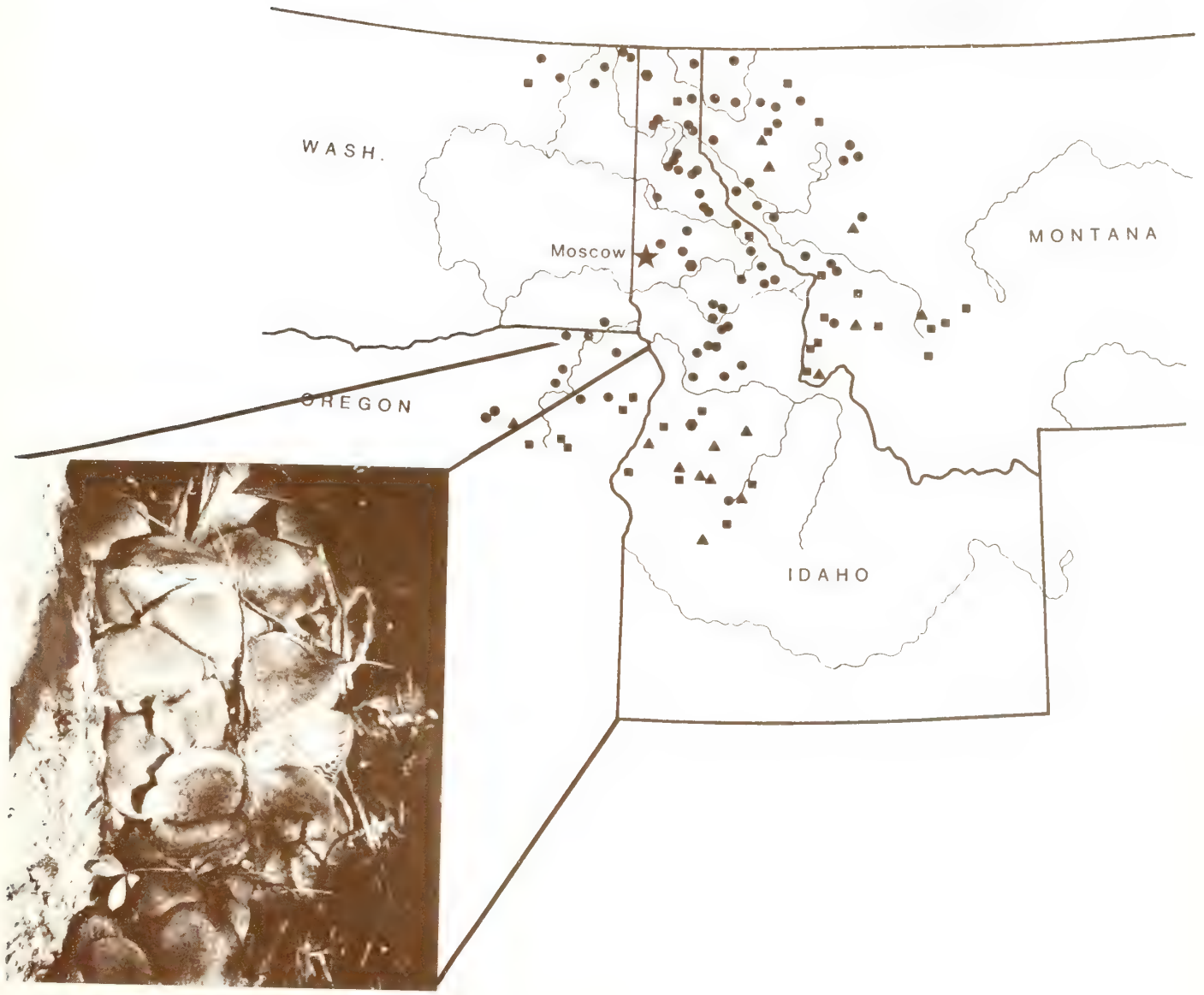
Forest Service

**Intermountain
Research Station**

Research Paper
INT-381

Occurrence of *Armillaria* spp. in Forests of the Northern Rocky Mountains

**Geral I. McDonald
Neil E. Martin
Alan E. Harvey**



THE AUTHORS

GERAL I. McDONALD is principal pathologist with the Intermountain Research Station's Genetics and Pest Resistance Research Work Unit in Moscow, ID. He received a B.S. degree in forest management (1963) and Ph.D degree in plant pathology (1969) from Washington State University. Since joining the Station in 1966, he has studied the epidemiology and genetic interaction of the blister rust organism and its hosts. He is now studying the ecological genetics of conifer-*Armillaria* interactions.

NEIL E. MARTIN is research plant pathologist with the Intermountain Research Station's Silviculture and Pathology Research Work Unit in Moscow, ID. He received a B.S. degree in botany (1961) from Iowa State University, an M.S. degree in plant pathology (1964) from South Dakota State University, and a Ph.D. degree in plant pathology (1972) from Washington State University. Since joining the Station in 1966, he has studied blister rust, dwarf mistletoe, and root rot.

ALAN E. HARVEY is principal plant pathologist with the Intermountain Station's Forestry Sciences Laboratory in Moscow, ID. He received a B.S. degree in biology (1960), an M.S. degree in plant pathology (1962), and a Ph.D. degree in plant pathology (1968). He completed one academic year of postgraduate work in plant pathology in 1972.

RESEARCH SUMMARY

The distribution of *Armillaria* spp. on National Forests of the Northern Rocky Mountains was investigated through random installation and inspection of 0.04-ha plots. Woody plant species living and dead were searched for fans, rot, or rhizomorphs typical of *Armillaria* spp., which were then verified through laboratory cultures. *Armillaria* occurrence was found to be related to a root rot risk-rating system based on the current system for classifying vegetational communities. *Armillaria* spp. were absent from the warm and dry juniper and pinegrass habitat types (h.t.'s) of the Douglas-fir series, the cold and dry beargrass and grouse whortleberry h.t.'s of the subalpine fir series, the cold and wet twisted stalk h.t.'s of the subalpine fir series, and the frost-pocket dwarf huckleberry h.t.'s of both the Douglas-fir and subalpine fir series.

Data linking *Armillaria* spp. to host and ecological function (epiphyte, saprophyte, or pathogen) were also recorded. These data will be reported in future papers after more reliable methods have been developed for assigning isolates to their correct taxonomic positions. We expect to find that certain *Armillaria* spp. are pathogenic on conifers in general or maybe even on specific conifer species, and that their geographic distribution is related to habitat type.

August 1987
Intermountain Research Station
324 25th Street
Ogden, UT 84401

Occurrence of *Armillaria* spp. in Forests of the Northern Rocky Mountains

Geral I. McDonald
Neil E. Martin
Alan E. Harvey

INTRODUCTION

Root disease caused by various species of *Armillaria* is integral to most forested ecosystems worldwide (Wargo and Shaw 1985). As early as 1930, the fungus was recognized as a root pathogen in the Western United States (Hubert 1931, 1950; Johnson 1976). *Armillaria* commonly occurs as rootlike rhizomorphs growing on plant debris or is epiphytically attached to root systems of dead, diseased, or healthy host plants (Garrett 1960; Kile 1980; Leach 1939; Raabe and Trujillo 1963; Redfern 1973). Isolates obtained from such rhizomorphs, as well as isolates obtained from mycelial fans, rotten wood, and sporophores, can belong to species or specific clones whose apparent pathogenicity varies (Kile 1983; Rishbeth 1982; Wargo and Shaw 1985).

Severity of this root disease tends to increase as management intensifies. Partial cutting (Filip 1977; Filip and Goheen 1982; Redfern 1978), excessive grazing (Bega 1979), and fire control (Shaw and others 1976) all appear linked to increased activity of *Armillaria* spp. In Queensland, Australia, *Armillaria* spp. were found in nearly all stumps after clearcutting of a first-rotation introduced pine forest (Anon. 1982). Chemical and mechanical killing of hardwoods is linked to increased *Armillaria* activity (Pronos and Patton 1977; Swift 1972) in remaining conifers. Conifers planted to replace clearcut conifer or hardwood forests have experienced significant *Armillaria*-related mortality (Redfern 1978; Shaw and Roth 1978). *Armillaria* spp. frequently interact with insects and other pathogens (Dunbar and Stephens 1975; Madziara-Borusiewicz and Strzelecka 1977; Singh and Raske 1983; Wargo 1977, 1981) to compound losses. Slash disposal methods may also affect *Armillaria* spp.; woody debris incorporated into the soil can be a significant source of new infections (Garrett 1960; Raabe and Trujillo 1963). Even method and quality of planting (Rykowski 1981) can influence damage caused by this organism (Singh and Richardson 1973).

Aside from total removal of woody plant parts followed by clean cultivation, no technique has proved effective in controlling this pathogen (Pawsey 1973; Shaw and Roth 1978). Other promising management techniques are the planting of tolerant or resistant species or varieties; application of chemicals or fire; site amendments (including extraction of wood from the soil) prior to planting; and judicious selection of cutting times based on overall risk prediction. Effective application of such techniques requires much new knowledge of the biology, genetic architecture, physiology, and ecology of hosts and the causal agent. We particularly need to know variation in pathogenicity and virulence of the pathogen and variation in resistance of the hosts.

Many studies have reported that in terms of geographic distribution and host range, *Armillaria* spp. are ubiquitous (Ehrlich 1939; Hobbs and Partridge 1979; Hubert 1950; Swift 1972). The primary objective of such studies has been to determine the degree of its damage rather than the distribution of the fungus. Typical examples are Carey and others (1984), Williams and Marsden (1982), and James and others (1984), wherein sample points were selected by location of symptomatic trees or root disease centers.

What do we need to know about *Armillaria*? How extensive is the distribution of various species of *Armillaria* and to what extent are these species pathogenic or saprophytic? Useful information could also include host, pathogenic or saprophytic condition, and taxonomic affiliation of each fungal sample. Knowing probability of occurrence (such as a proportion of 0.04-ha plots) of pathogenic and nonpathogenic entities in relation to other ecological criteria could serve as the basis for classifying forest lands according to risk of specific host species, given various management actions. Control measures could be similarly categorized.

In 1983, we began a study of population level genetic and ecological interactions between *Armillaria* and its conifer and hardwood hosts. The two primary objectives of this research were (1) to predict *Armillaria* risk by habitat type, host species, and stand management history; and (2) to develop ways for assessing genetic and physiologic responses between host and fungus populations in Northern Rocky Mountain forests. This paper reports on the occurrence of vegetative parts of *Armillaria* spp. by climax series.

MATERIALS AND METHODS

Plots 0.04 ha in size were randomly selected from forested lands of the Northern Rocky Mountains as follows: A 1.27-cm grid was placed over 1,270-cm:1,609-m maps of 15 Northern Rocky Mountain National Forests. Random coordinates were drawn 15 times for each National Forest to locate 15 sections (1,609-m^2 blocks) on each. Aerial photo indexes were used to obtain 12,000:1, 16,000:1, or 24,000:1 photos of the selected sections. Each photo was matched in turn with drainage patterns and other features common to the photos and maps for locating the target

section. Section lines were drawn to scale on the photograph and measured in millimeters. Next, two random numbers were chosen between 1 and the scaled length (about 100 mm, dependent on photo scale) of a section border. The northwestern corner of the section was used as the zero intersection on which to locate the randomly drawn coordinates. The point described by the coordinates was used as the plot center.

Plots were selected according to two criteria: (1) site must be forested or have once supported forests, and (2) site must be less than 1.6 km from a trail or road. Plots were selected in the order that sections were selected, eight plots per National Forest. If the first selection was unsuitable, then a ninth plot was selected. This process was continued until all 15 sections within a National Forest were used. If eight satisfactory plots were not found, then the first discarded section was used again, with the northeastern corner as the zero intersection for the randomly drawn coordinates. The process continued until eight satisfactory plots were obtained on each of the 15 National Forests.

A line was drawn from the plot point on the photo to a landmark along a road or trail. This became the witness point. The distance between witness point and plot was scaled from the photo.

In the field, the photo was oriented, and the bearing from the witness point to the plot was obtained from the photo and recorded. A string-line recorder was used to measure (nearest meter) the scaled distance from the witness point to the plot, and a compass was used to follow the designated bearing. If a stream or some other impassable barrier blocked the chosen path to the designated plot, the complementary bearing and distance were taken in the opposite direction. In a few cases, the designated distance was halved for the same reason. Ultimately, the main criterion was that the plot be located at the end of a measured line of predetermined length. The eight randomly chosen plots per National Forest provided a total of 120 plots. An additional 19 auxiliary plots were taken in areas where *Armillaria* spp. were not found on random plots. This provided a more encompassing sample for future study of geographic variation of the fungus and enhanced our knowledge of specific occurrence patterns.

After traveling the designated distance, a plot center was established at a tree or other major feature. Using a compass and a string-line recorder, a plot 20 m on a side (400 m^2) was laid out with sides parallel and perpendicular to the bearing. Key indicator plants were recorded, as were aspects of topography, so that habitat type (based on potential climax vegetation) of the plot could be determined (Pfister and Arno 1980). The vegetation was photographed. Roots of cut trees, wind-broken trees, and dead trees (from seedling to mature) were inspected for rhizomorphs, fans, characteristic rotten wood, and root resinosis. The root systems of at least one living and apparently healthy representative of all major hardwood and conifer species on the site were inspected for fans, rotten wood, and attached rhizomorphs. The inspection consisted of exposing the root collar and major roots to a depth of about 0.3 m and a lateral spread of 0.5 to 1 m, then looking for rot and fans by chopping. Living and apparently healthy conifers that were selected for increment boring (cores to be used later to study relationships between *Armillaria* activity and site productivity) were also inspected for fans, resinosis, and attached rhizomorphs. These trees were thoroughly inspected around half their root crowns and along all major roots attached to the inspected portion. This inspection required 1 to 3 hours to complete. Any insect or disease problems were also noted.

Sections of rhizomorphs 0.1 to 0.5 m in length were collected and their source recorded. They had to be physically attached to the host plant to be recorded as being from that host. Rhizomorphs not so attached were recorded as taken from the soil. The samples were placed in disposable plastic culture tubes and taken to a field laboratory (motel room). Each evening the day's collections (rhizomorphs, bark fans, or rotten wood) were rinsed two times in tap water, then sterilized for 10 minutes in a 20 percent commercial bleach solution. The bleach solution was decanted and collections rinsed by filling the tube with sterilized water, vigorously agitating, and decanting. They were rinsed a second time and allowed to set for 10 minutes. The final rinse was decanted, and sterilized rhizomorphs were removed and cut into 5- to 10-mm segments. These were placed, one each, in 10-mL plastic culture tubes containing 1.5 percent malt extract medium. After 1 month, all collections were verified for rhizomorph production in culture as well as other cultural attributes typical of the genus *Armillaria*. Some fans were taken directly from their underbark location and placed in the 10-mL tubes.

All plots were classified by habitat type with dichotomous keys based on lists of indicator plants (Cooper and others in press; Pfister and others 1977; Steele and others 1981). This classification was verified by an ecologist through study of the plot photos and plant lists. Habitat type of the few plots that occurred on fresh or regenerated clearcuts was determined by inspection of adjacent stands. The plots were lumped by climax series for some analyses and by habitat type for others. The proportion of *Armillaria* occurrence on any host and as epiphytic rhizomorphs on hardwoods and conifers was calculated. Also calculated was the proportion of epiphytic rhizomorphs found on: (1) healthy conifers by species, (2) healthy hardwoods (including dead parts of healthy plants), and (3) dead conifer materials by plot.

RESULTS

Armillaria Distribution

Chi-square analysis of the climax series revealed significant heterogeneity regarding the probability of encountering *Armillaria* on randomly selected 0.04-ha plots (table 1). Heterogeneity seemed to be associated with plot productivity, as measured by average site index (height of dominant and codominant trees at 50 years = SI in table 1). We therefore arrayed the plots by habitat type in order of increasing productivity within climax series (table 2). The two least productive series (ABLA and PSME)(see table 2 footnote for species code definitions) showed a definite discontinuous distribution pattern. Hot-dry, cold-dry, and frost-pocket habitat types appeared not to support *Armillaria*. Two plots on cold-wet habitat types (ABLA/STAM and ABLA/CACA) also failed to yield

Table 1—Incidence of *Armillaria* spp. signs and/or symptoms on randomly selected 0.04-ha plots classified by climax vegetation series on 15 Northern Rocky Mountain National Forests

Climax indicator	Average site index[1]	Number of plots	Number with *Armillaria*	Proportion with *Armillaria*
Subalpine fir	16.15	[2]35	15	0.42
Douglas-fir	16.46	[3]18	6	.33
Grand fir	19.81	42	33	.79
Western redcedar	21.95	10	10	1.00
Western hemlock	22.56	15	14	.93

χ^2 = 29.38, d.f. = 4, prob. of larger χ^2 = 0.0005.

[1]Average height at 50 years (meters) of all conifer species in the series obtained from Cooper and others (in press); Pfister and others (1977); Steele and others (1981).

[2]Includes the single mountain hemlock series plot.

[3]Includes the single ponderosa pine series plot.

Armillaria. The distribution on the more productive series seems essentially continuous (table 2). Within the grand fir series, two habitat types characterized as hot-dry (CARU and SPBE) failed to yield *Armillaria*. Of the 60 remaining plots, only two (one ABGR/CLUN and one TSHE/CLUN) failed to yield *Armillaria*.

There was good continuity between habitat types where *Armillaria* was and was not found, regardless of geographic location. For example, *Armillaria* was absent from cold-dry habitat types (ABLA/VASC and ABLA/XETE) on both northern (Flathead, Kootenai, Lolo, and St. Joe) and southern (Payette, Boise, and Wallowa-Whitman) National Forests. On the other hand, if one of the habitat types that supported *Armillaria* elsewhere (for instance, ABLA/CLUN) occurred near ABLA/VASC or ABLA/XETE, *Armillaria* was present as shown by the triangles (auxiliary plots with, random plots without) on figure 1.

Epiphytic Rhizomorphs

When *Armillaria* was found, records included presence or absence of typical rot, fans, and rhizomorphs. Quantitative data about rhizomorph biomass were not recorded, but variation in the ease of finding rhizomorphs was evident.

Rhizomorph occurrence on living hardwoods (or dead portion of a living clump), dead conifers, and the various species of living conifers showed significant variation by chi-square analysis (table 3). Rhizomorphs were found on about 40 percent of the healthy conifer root systems of sapling or larger sized trees. There were also significant differences between conifer species (significant heterogeneity chi-square in table 4), particularly with Douglas-fir and grand fir.

Table 2—Delineated habitat types and status of *Armillaria* spp. on 120 0.04-ha plots randomly located within 15 National Forests of the Northern Rocky Mountains

Habitat type[1]	Average site index[2]	Climatic characterization	Number of plots	Percentage with *Armillaria*
PIPO/SYAL	15.5	Hot and dry	1	0
PSME/JUCO	9.8	Hot and dry	2	0
PSME/VAGL	14.9	Cool and dry	2	100
PSME/CARU	15.2	Hot and dry	6	0
PSME/VACA	16.2	Frost pocket	1	0
PSME/PHMA	17.7	Warm and dry	6	67
ABLA/VASC	12.8	Cold and dry	8	0
ABLA/MEFE	14.3	Cold and moderate	6	83
ABLA/ALSI	14.6	Cold and moderate	2	100
ABLA/VAGL	14.9	Cool and dry	3	100
ABLA/VACA	15.2	Frost pocket	2	0
ABLA/XETE	15.8	Cold and dry	6	0
ABLA/CACA	17.4	Cold and wet	1	0
ABLA/ACGL	18.0	Cool and dry	1	100
ABLA/CLUN	19.8	Cool and moderate	5	80
ABLA/STAM	21.9	Cold and wet	1	0
ABGR/LIBO	16.5	Warm and dry	3	67
ABGR/CARU	18.0	Hot and dry	1	0
ABGR/XETE	18.6	Cool and moderate	5	100
ABGR/VAGL	19.2	Cool and dry	5	100
ABGR/CLUN	21.0	Cool and moderate	12	92
ABGR/PHMA	22.3	Warm and dry	6	100
ABGR/ASCA	22.6	Cool and moderate	4	100
ABGR/SPBE	24.1	Hot and dry	6	0
THPL/ASCA	21.3	Warm and moderate	3	100
THPL/ATFI	21.6	Warm and wet	1	100
THPL/CLUN	21.9	Warm and moderate	3	100
THPL/ADPE	23.5	Warm and wet	3	100
TSHE/CLUN	22.6	Warm and moderate	11	91
TSHE/GYDR	22.9	Warm and wet	1	100
TSHE/ASCA	23.8	Warm and moderate	3	100

[1]Species identification: PIPO = *Pinus ponderosa*, PSME = *Pseudotsuga menziesii*, ABLA = *Abies lasiocarpa*, ABGR = *Abies grandis*, THPL = *Thuja plicata*, TSHE = *Tsuga heterophylla*, SYAL = *Symphoricarpus albus*, JUCO = *Juniperus communis*, VAGL = *Vaccinium globulare*, CARU = *Calamagrostis rubescens*, VACA = *Vaccinium caespitosum*, PHMA = *Physocarpus malvaceus*, VASC = *Vaccinium scoparium*, MEFE = *Menziesia ferruginea*, ALSI = *Alnus sinuata*, XETE = *Xerophyllum tenax*, CACA = *Calamagrostis canadensis*, ACGL = *Acer glabrum*, CLUN = *Clintonia uniflora*, STAM = *Streptopus amplexifolius*, LIBO = *Linnaea borealis*, ASCA = *Asarum caudatum*, SPBE = *Spiraea betulifolia*, ATFI = *Athyrium felix-femina*, ADPE = *Adiantum pedatum*, GYDR = *Gymnocarpium dryopteris*.

[2]Average height at 50 years (meters) of all conifer species in the series obtained from Cooper and others (in press); Pfister and others (1977); Steele and others (1981).

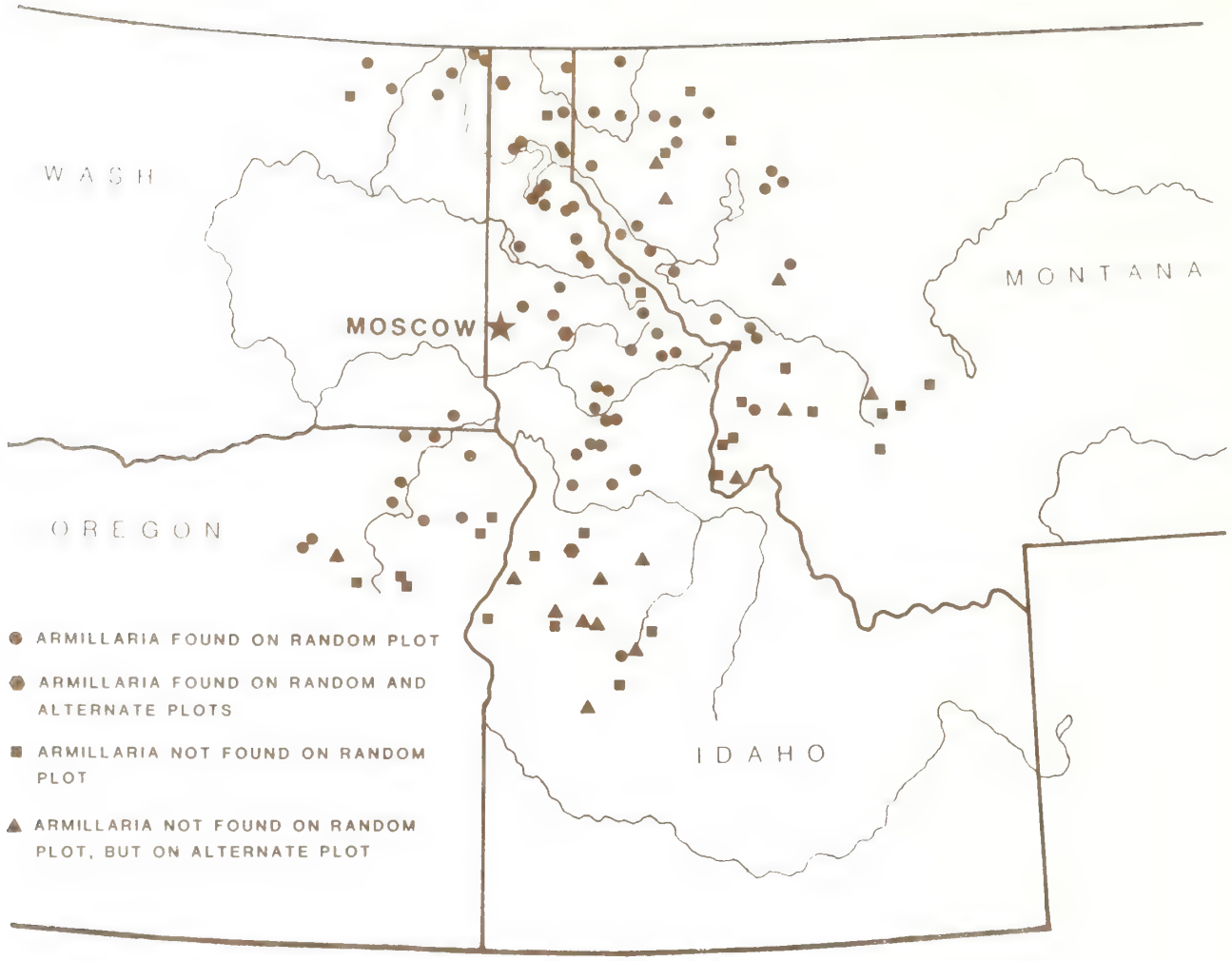


Figure 1—Location of *Armillaria* survey plots installed in 1983.

Table 3—Incidence of *Armillaria* spp. rhizomorphs on healthy and dead conifers or healthy hardwoods growing on randomly located 0.04-ha plots within habitat types supporting *Armillaria* spp. in Northern Rocky Mountain National Forests

Materials	Number plants inspected	Number with rhizomorphs	Proportion with rhizomorphs
Healthy hardwoods	203	162	0.80
Dead conifers	110	95	.86
Healthy conifers	380	164	.43

χ^2 = 107.48, d.f. = 2, prob. of larger χ^2 = 0.0005.

Table 4—Incidence of culturally verified *Armillaria* spp. rhizomorphs on healthy conifers growing within habitat types supporting *Armillaria* spp.

Conifer species	Number plants inspected	Number with rhizomorphs	Proportion with rhizomorphs
Ponderosa pine	18	6	0.33
Lodgepole pine	39	12	.31
White pine	19	6	.32
Douglas-fir	72	39	.54
Western larch	51	22	.43
Western hemlock	14	8	.36
Western redcedar	25	5	.20
Engelmann spruce	50	16	.32
Grand fir	61	39	.64
Subalpine fir	31	11	.35

χ^2 = 26.33, d.f. = 9, prob. of larger χ^2 = 0.005.

DISCUSSION

Geographic Distribution

Habitat type identification to characterize plant communities is becoming a standard tool of forest management in the Inland West. The techniques of vegetation analysis are well documented (Cooper and others in press; Pfister and others 1977; Steele and others 1981). In this study, we applied these techniques to the analysis of vegetation on 400-m^2 plots. In a few cases, where vegetation indicated a habitat undefined for that region, we applied habitat type definitions from adjacent forests, providing that other evidence also supported a correspondence of habitat types.

The dichotomy observed in this study between presence and absence of *Armillaria* agrees in general with findings in Australia (Kile 1980, 1981) where Australian *Armillaria* spp. also did not occur on very dry sites. In this study, the warmest and driest habitat types of the PSME series, as well as coldest and driest habitat types of the ABLA series and the "frost pocket" sites exemplified by the ABLA/VACA and PSME/VACA habitat types, did not seem suitable for *Armillaria*. The absence of *Armillaria* from the two cold-wet sites (ABLA/CACA and ABLA/STAM) indicates that both excessive cold and excessive moisture might limit growth and development of *Armillaria*.

The presence-absence dichotomy of *Armillaria* spp. occurrence prevailed when we examined moist auxiliary plots adjacent to dry or cold random plots (see fig. 1 for location of auxiliary plots). Also, the occurrence of *Armillaria* on all of the plots randomly located on the Coeur d'Alene, Clearwater, and Nez Perce National Forests, an area of approximately 5 million acres, reinforces these ideas. The five instances of discontinuous distribution (one plot in each of ABLA/MEFE, ABLA/CLUN, ABGR/LIBO, ABGR/CLUN, and TSHE/CLUN), where continuous distribution was expected, could be attributed to misidentified habitat type, a transitional state between suitable and unsuitable habitat types, or stand history (possibly wildfire) that prevented establishment of the fungus or recently eradicated it. The ABLA/MEFE plot was probably in transition to the ABLA/XETE habitat type, and the ABGR/LIBO could be transitional to ABGR/CARU. Influential factors of stand history are a particularly attractive explanation of the absence of the fungus from the ABLA/CLUN and ABGR/CLUN plots because the two fir series plots were located about 1,600 m apart in the same drainage of western Montana. We have no ready explanation for the absence of *Armillaria* from one TSHE/CLUN plot.

The evidence from this study concerning *Armillaria* spp. distribution can be summarized in the following hypothesis: Any 0.04-ha plot of forest land in the TSHE and THPL series located in the Northern Rocky Mountains will yield *Armillaria*. All the ABGR series in this region, except the SPBE and CARU habitat types, will also yield *Armillaria*. Greater discontinuity exists within the ABLA and PSME series. Only two PSME habitat types support *Armillaria*; these are VAGL and PHMA. In fact, the limiting conditions may be at the phase level within these habitat types. Four ABLA series habitat types support *Armillaria*. These are ALSI (*Alnus sinuata*), VAGL (*Vaccinium globulare*), MEFE (*Menziesia ferruginea*), and CLUN (*Clintonia uniflora*); however, they may show discontinuities at the phase level. We further hypothesize that *Armillaria* is absent from both the ponderosa and limber pine (*Pinus flexilis*) series. *Armillaria* spp. will behave in the mountain hemlock (*Tsuga mertensiana*) series as they do in the ABLA series. We have no information about the Engelmann spruce series.

Epiphytic Rhizomorphs

Our frequency of encountering epiphytic rhizomorphs is similar to that of Kile (1980, 1981), who encountered epiphytic rhizomorphs on 85 percent of the dead eucalypts (stumps, fire killed, and so forth) inspected. We found rhizomorphs on 86 percent of the dead conifers inspected on habitat types that supported the fungus. He found 20 percent of 202 healthy eucalypts supporting epiphytic rhizomorphs. We found 43 percent of the healthy conifers and 80 percent of the healthy hardwoods (or dead portions of healthy clumps) supporting epiphytic rhizomorphs. These values are based on a large sample and therefore provide good estimates of the probability of encountering epiphytic rhizomorphs on these materials in the Inland West in habitat types suitable for *Armillaria*.

CONCLUSIONS

Results presented in this paper indicate that risk to *Armillaria* spp. in the Northern Rocky Mountains can be predicted by habitat type. The cold-dry and hot-dry sites seemingly are outside the ecological range of all forms of *Armillaria* native to the Northern Rocky Mountains. These hypothesized patterns of occurrence must be validated before being put to general use for predicting risk of *Armillaria* root rot. This technique of risk prediction has potential application throughout the Western United States, both for *Armillaria* and for other endemic diseases of forest trees. This approach could be particularly effective for predicting the range and presence of root pathogens of woody plants. The occurrence and function of these fungi are likely tied to long-term soil and climatic conditions, similar to the occurrence of indicator plants.

Perfecting a risk-prediction system will entail additional research. We must do more fieldwork to learn the geographic and host ranges of *Armillaria* spp. clones. This will enhance our knowledge of ecological genetics of the *Armillaria*-conifer interaction. We must also taxonomically classify *Armillaria* clones. Effective progeny testing awaits development of techniques to measure host vigor and susceptibility, along with fungus pathogenicity. Regardless of the ultimate findings of such research, the findings reported here clearly indicate that forest managers will need to know habitat type of stands in the Northern Rockies if they are to account for potential *Armillaria* damage in their management plans.

REFERENCES

Anon. 1982. Forest pathology - conifer plantation. In: Report on research activities for 1980-81. Australia: Division Technical Services, Queensland Department of Forestry: 52-53.

Bega, R. V. 1979. Heart and root rot fungi associated with deterioration of *Acacia koa* on the island of Hawaii. Plant Disease Reporter. 63: 682-684.

Carey, A. C.; Miller, E. A.; Geballe, G. T.; Wargo, M.; Smith, W. H.; Siccama, T. G. 1984. *Armillaria mellea* decline of red spruce. Plant Disease. 68: 794-795.

Cooper, S. T.; Neiman, K. E.; Steele, R. [In press]. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Dunbar, D. M.; Stephens, G. R. 1975. Association of two-lined chestnut borer and shoestring fungus with mortality of defoliated oak in Connecticut. Forest Science. 21: 169-174.

Ehrlich, J. 1939. A preliminary study of root disease in western white pine. Station Paper 1. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Rocky Mountain Forest and Range Experiment Station. 10 p.

Filip, G. M. 1977. An *Armillaria* epiphytic on the Winema National Forest, Oregon. Plant Disease Reporter. 61: 708-711.

Filip, G. M.; Goheen, D. J. 1982. Tree mortality caused by root pathogen complex in Deschutes National Forest, OR. Plant Disease. 66: 240-243.

Garrett, S. D. 1960. Rhizomorph behavior in *Armillaria mellea* (Fr) Quel. III. Saprophytic colonization of woody substrates in soil. Annals of Botany. 24: 275-285.

Hobbs, S. D.; Partridge, A. D. 1979. Wood decays, root rot, and stand composition along an elevation gradient. Forest Science. 25: 31-42.

Hubert, E. E. 1931. An outline of forest pathology. New York: John Wiley and Sons. 543 p.

Hubert, E. E. 1950. Root rot of the western white pine type. Northwest Science. 24: 5-17.

James, R. L.; Stewart, C. A.; Williams, R. E. 1984. Estimating root disease losses in northern Rocky Mountain National Forests. Canadian Journal of Forest Research. 14: 652-655.

Johnson, D. W. 1976. Incidence of disease in National Forest plantations in the Pacific Northwest. Plant Disease Reporter. 60: 883-885.

Kile, G. A. 1980. Behavior of an *Armillaria* in some *Eucalyptus obliqua* - eucalyptus regions forests in Tasmania and its role in their decline. European Journal of Forest Pathology. 10: 278-296.

Kile, G. A. 1981. *Armillaria luteobubaline*: a primary cause of decline and death of trees in mixed species eucalypt forests in central Victoria. Australian Forest Research. 11: 63-77.

Kile, G. A. 1983. Identification of genotypes and the clonal development of *Armillaria luteobubaline* (Watling and Kile) in eucalypt forests. Australian Journal of Botany. 31: 657-671.

Leach, R. 1939. Biological control and ecology of *Armillaria mellea* (Wahl) Fr. Transactions of the British Mycological Society. 287: 320-329.

Madziara-Borusiewicz, K.; Strzelecka, H. 1977. Conditions of spruce (*Picea excelsa* Lk.) infestation by the engraver beetle (*Ips typographus* L.) in mountains of Poland. I. Chemical composition of volatile oils from healthy trees and those infested with the honey fungus (*Armillaria mellea* [Vahl] Quel). Zeitschrift fuer Angewandte Entomologie. 83: 409-415.

Pawsey, R. G. 1973. Honey fungus: recognition, biology and control. The Agricultural Association Journal. 2: 116-126.

Pfister, R. D.; Arno, S. F. 1980. Classifying forest habitat types based on potential climax vegetation. Forest Science. 26: 52-70.

Pfister, R. D.; Kovalchik, B. L.; Arno, S. F.; Presby, R. C. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 174 p.

Pronos, J.; Patton, R. F. 1977. *Armillaria* root rot of red pine planted on oak sites in Wisconsin. Plant Disease Reporter. 61: 955-958.

Raabe, R. D.; Trujillo, E. J. 1963. *Armillaria mellea* in Hawaii. Plant Disease Reporter. 47: 776.

Redfern, D. B. 1973. Growth and behavior of *Armillaria mellea* rhizomorphs in soil. Transactions of the British Mycological Society. 61: 569-581.

Redfern, D. B. 1978. Infection of *Armillaria mellea* and some factors affecting host resistance and the severity of disease. Forestry. 15: 121-135.

Rishbeth, J. 1982. Species of *Armillaria* in southern England. Plant Pathology. 31: 9-17.

Rykowski, K. 1981. The influence of fertilizers on the occurrence of *Armillaria mellea* in Scots pine plantations. European Journal of Forest Pathology. 11: 108-119.

Shaw, C. G., III; Roth, L. F. 1978. Control of *Armillaria* root rot in managed coniferous forests: a literature review. European Journal of Forest Pathology. 8: 163-174.

Shaw, C. G., III; Roth, L. F.; Rolph, L.; Hunt, J. 1976. Dynamics of fire and pathogen as they relate to damage in a forest attacked by *Armillaria*. Plant Disease Reporter. 60: 214-218.

Singh, P.; Raske, A. G. 1983. *Armillaria* root rot in spruce-budworm-damaged balsam fir stands. In: CANUSA Newsletter 26. Washington, DC: U.S. Department Agriculture, Forest Service: 2.

Singh, P.; Richardson, J. 1973. *Armillaria* root rot in seeded and planted areas in Newfoundland. Forestry Chronicle. 49: 180-182.

Steele, R.; Pfister, R. D.; Kittams, J. A. 1981. Forest habitat types of central Idaho. Gen. Tech. Rep. INT-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 138 p.

Swift, M. J. 1972. The ecology of *Armillaria mellea* Vahl. (en Frier) in the indigenous and exotic woodlands of Rhodesia. Forestry. 45: 67-86.

Wargo, P. M. 1977. *Armillaria mellea* and *Agrilus hilineatus* and mortality of defoliated oak trees. Forest Science. 23: 485-492.
Wargo, P. M. 1981. Defoliation and secondary-action organism attack: with emphasis on *Armillaria mellea.* Journal of Arboriculture. 7: 64-69.
Wargo, P. M.; Shaw, C. G., III. 1985. *Armillaria* root rot—the puzzle is being solved. Plant Disease. 69: 826-832.
Williams, R. E.; Marsden, M. A. 1982. Modeling probability of root disease center occurrence in northern Idaho forests. Canadian Journal of Forest Research. 12: 876-882.

McDonald, Geral I.; Martin, Neil E.; Harvey, Alan E. 1987. Occurrence of *Armillaria* spp. in forests of the Northern Rocky Mountains. Res. Pap. INT-381. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 7 p.

Random sampling on 15 National Forests in the Northern Rocky Mountains revealed that *Armillaria* spp. were absent from cold-dry and hot-dry habitat types and were nearly always present in the cool-moist to warm-moist habitat types.

KEYWORDS: root rot, plant pathology, forest management

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

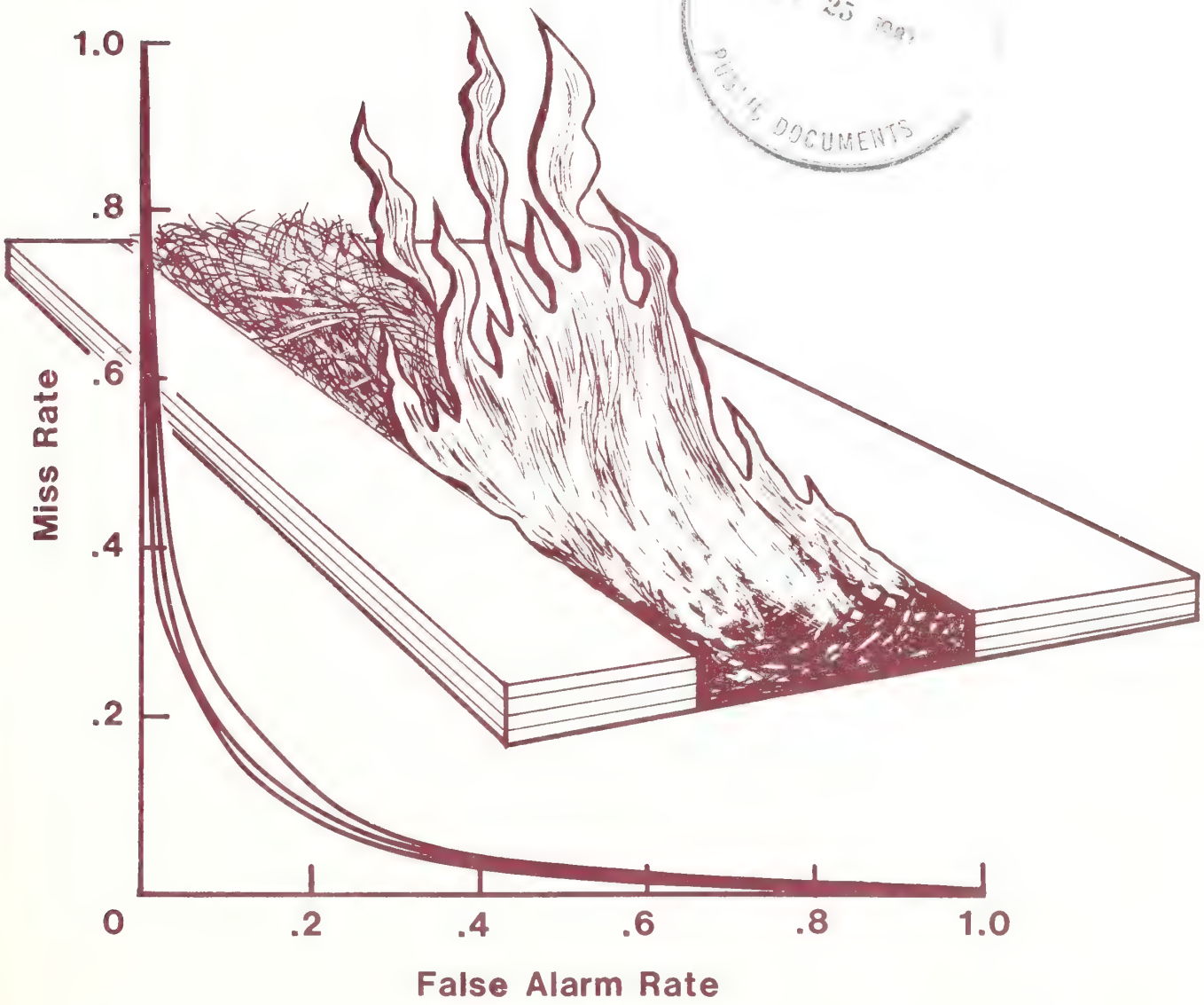
**Intermountain
Research Station**

Research Paper
INT-382

A Theoretical Basis for Modeling Probability Distributions of Fire Behavior

Ralph A. Wilson, Jr.

NOV 25 1987
PUBLIC DOCUMENTS



THE AUTHOR

RALPH A. WILSON is a research physicist assigned to the Fire Behavior research work unit at the Intermountain Fire Sciences Laboratory, Missoula, MT. His undergraduate studies in mathematics and physics were at Willamette University, Salem, OR (B.A. 1956), and his graduate work was in spectroscopy at University of Oregon, Eugene (M.A. 1958). He worked in infrared detectors and optics at the Naval Ordnance Test Station (now Naval Weapons Center), China Lake, CA, from 1957 to 1964. From 1964 to 1975, he worked on the Forest Service's airborne infrared forest fire surveillance project at the Northern Forest Fire Laboratory (now Intermountain Fire Sciences Laboratory).

RESEARCH SUMMARY

A method for predicting a range or distribution of expected fire behavior is developed to help fire managers weigh options. A fire model of marginal burning states produces "likelihood" distributions for the expected fire states. These distributions depend only on the current site observations and are independent of the prior fire state history of the site of application.

Using elementary decision theory, a fire manager first chooses a fire state prescription for the site to be burned. Then, from an appropriate decision goal and the prior distribution of the prescribed state, a threshold value of the likelihood for that fire state is calculated and used to decide whether the site conditions are within the burn prescription, thence whether to burn or not burn.

Two types of error rates are calculated for the marginal burning states: the probability that a fire might burn when predicted to not burn and the probability that it might not burn when predicted to burn. A parametric plot of the two error rates is used as a test of the marginal fire state model and demonstrates the model's utility.

September 1987

Intermountain Research Station
324 25th Street
Ogden, UT 84401

A Theoretical Basis for Modeling Probability Distributions of Fire Behavior

Ralph A. Wilson, Jr.

INTRODUCTION

In recent years great progress has been made in applying fire behavior models in fire management systems nationwide—in several cases, worldwide. Similarly, these fire models have provided fire intelligence for an unanticipated variety of administrative decision and planning functions.

The wide acceptance, and particularly the unique situations to which these models have been applied, has caused problems to arise in two interrelated areas: first, it has been necessary to adjust and "fine-tune" fire behavior systems to properly respond to different geographic locations, and second, the resultant fire behavior information provided is often insufficient, inappropriate, or misleading in some special applications. Both problems would be greatly reduced by developing a definitive method of estimating uncertainties, calculating risks of error, or forecasting a range of possible fire behavior.

This paper documents a theoretical basis for implementing predictive distributions of fire behavior and is intended primarily for the use of specialists who design wildland fire models and systems for applying them. Although Bayesian methods are used, the idea is **not** to specifically recommend a Bayesian Decision System, but rather to show how predictive distributions could be used by the decision makers to specify the inherent limitations of predictive systems, to suggest methods for system optimization for specific applications, and to demonstrate procedures for testing a model's performance. I have tried to "keep it simple" in order to get basic ideas across; thus, I ignore such niceties as distinguishing between continuous and discrete distributions, rigorous use of probability densities, etc., and I avoid complicated derivations.

The central theme of this discussion is that **the fire model** must be universally applicable because fire is a physical process governed by universal physical law; however, a fire model is an **approximation** of real-world fire behavior that implies a degree of uncertainty—uncertainty that must be understood by both the model designer and the manager using the model. Although a model has universal applicability, it is valid **only** within the domain and range of variables for which it is designed, tested, and verified.

In addition, it is emphasized that the prior historical frequency of any predicted fire state is unique to each locality, may be only qualitatively known by local "expert" observers, and is outside the predictive capability of a physical model of fire behavior.

The analysis and solution of these difficulties may be enhanced by using what are sometimes called "Bayesian" techniques—techniques that are quite controversial, yet having some analytical merit. The controversy centers on the admissability of subjective or personal opinion for estimating probabilities as a basis for decision making. Very strong conviction is held on both sides of the controversy: the modern Bayesian theorists emphasize the subjective **personal** decision characterized by the possessive nature of "his goal" and "his objective." In the following development, reference to subjective estimation is made where it may apply. The decision mechanics, risk, and error analysis techniques are reliable and standard engineering practice. These concepts will be illustrated using the following example.

EXAMPLE OF FIRE STATE MODEL AND OBSERVATIONS

In field application, a fire model is combined with **prior** knowledge of the local historical record to arrive at a **posterior** estimate (prediction) of events. The model itself requires **observations** of specific variables for the current conditions. (The terms "prior" and "posterior," respectively, refer to knowledge before and after the observations; "observer" refers to the manager-decision maker.)

Models are commonly constructed on the basis of **posterior** results of research experiments, but then improperly represented as posterior field predictions. Neglected is the fact that the **prior** conditions of the experiment are different from those in the field application! A properly designed model must express the likelihood that the current situation would be observed if, indeed, the given fire state would occur. When so designed, the fire model is independent of the "prior" conditions of the specific application and the experimental conditions from which it was developed.

It has been demonstrated (Wilson 1985) that the marginal limits of combustion may be represented to an observer as probabilistic distributions of "fire states." The distributions are functions of a parameter, n, which summarizes in a single number all current fuel **observations** and physically resembles a dimensionless burning rate; this parameter is a deterministic function of the physical fuel properties in a manner similar to traditional fire models:

$$n = \frac{\ln(\sigma\beta\delta\, h/Q_w)}{Q_{ig}/Q_w} \qquad (1)$$

where the nomenclature is similar to the original Rothermel (1972) model of fire spread:

- σ = fuel particle surface area to volume ratio
- β = fuel bed packing ratio, solid fuel volume/total bed volume
- δ = fuel bed depth
- h = heat of combustion of the fuel pyrolizate gases
- Q_{ig} = heat for pyrolysis (formerly heat of preignition) of fuel
- Q_w = heat of moisture desiccation (heat scaling factor).

The numerator of equation 1 represents the heat production rate of the fire and the denominator represents the energy needed to heat and pyrolize the fuel.

The burning **state** of a fire is only probabilistically determined even under the most elaborate experimental controls. Figure 1 shows the (posterior) experimental probability distributions for fire states, b_i and $\not b_i$. For purposes of this example, these fire states are defined by the fraction of fireline aflame:

- b_1 is the state with fraction of fireline aflame larger than zero
- $\not b_1$ is the state of fire that is out; $\not b$ is read "not b"
- b_2 is the state with fraction of fireline aflame larger than 0.5
- $\not b_2$ is the state with fraction of fireline aflame less than 0.5
- b_3 is the state with fraction of fireline aflame larger than 0.99
- $\not b_3$ is the state with fraction of fireline aflame less than 0.99.

In this example, the range of b is bounded with both upper and lower limits: at the lower limit by b_1, fires with zero percent of fireline aflame and at the upper limit by b_3 with 99 percent aflame. By this mechanism we were able to define and observe **marginal** burning.

In the discussion below, a fire state "window" is defined by the conjunction of two elementary states. For example, $b_z = (b_1, \not b_2)$ is the state with fraction of fireline greater than zero and less than 0.5. These fire states are defined in terms of an observable fire characteristic that might be related to a "fire effect," treatment, or prescription such as mineral soil exposure, fuel reduction, etc. Promising alternative fire states could be defined by fire intensity, flame length, or by spread rate itself, for example. The fire state as defined above will serve for illustration.

The results of Wilson's (1985) experiment with almost 500 fires, as shown in figure 1, are potentially misleading when applied to field problems. The results correctly show the fire state probability distributions, $P(b|n)$, **for the source experiment**. But that experiment was designed to examine fires near the limit of sustained combustion; thus, 38 percent of the test fires went out, $P(b_1) = 0.62$, 52 percent burned with more than half of the fireline aflame, $P(b_2) = 0.52$, and 32 percent burned with a full contiguous flame front, $P(b_3) = 0.32$. A resource manager

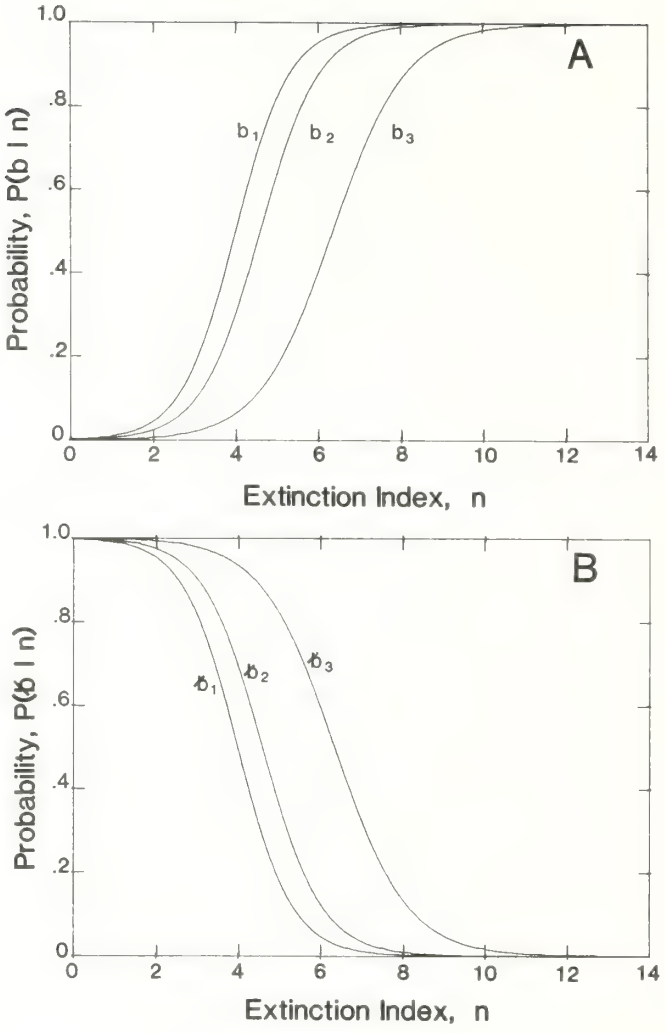


Figure 1—The posterior conditional probability distributions for the three marginal fire states defined in the text (after Wilson 1985).

is going to expect more than 62 percent of the brush fires in southern California in August to be self-sustaining.

The marginal frequency distribution of fire states, $P(b)$, (namely, the "prior" probability of b) in Wilson's experiment is unique to that experiment; that specific distribution is a consequence of the experimental design. Thus, the results plotted in figure 1 are "biased" by the design of the experiment and different results should be expected in other applications that will have different "prior" fire state probability distributions.

In the following discussion, the experimental results (fig. 1) are transformed into "likelihood ratios" (fig. 2) that measure the strength of the observational evidence, n, alone; this measure is independent of the prior probabilities and thus is more universally applicable. The review of decision theory and error analysis follows (Egan 1975). The illustrative example is the work of the author.

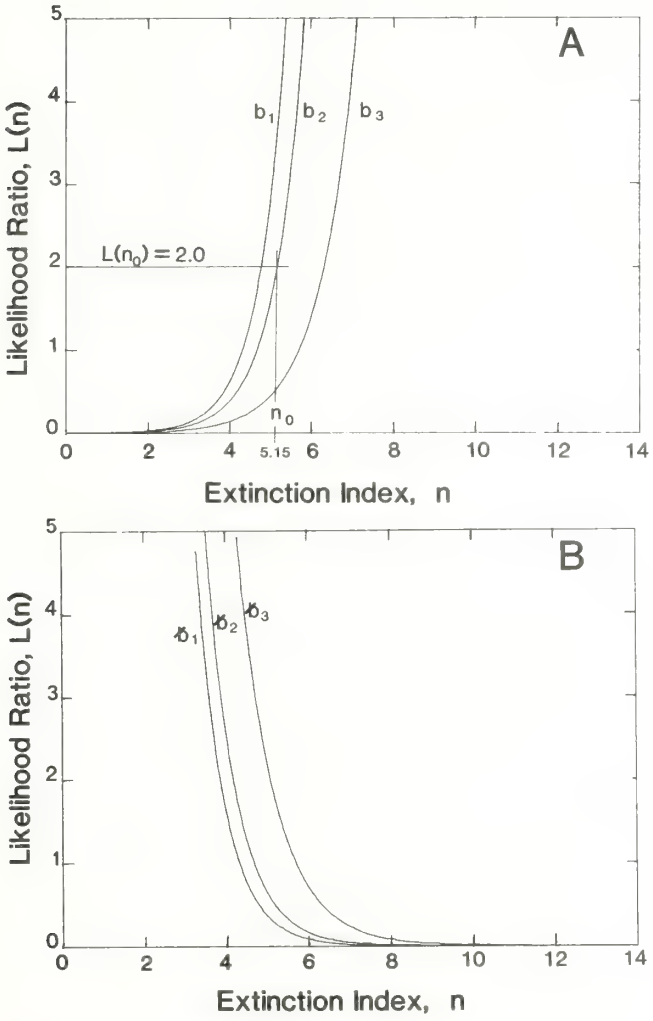


Figure 2—The likelihood ratios for the marginal fire states.

PROBABILITIES, DECISIONS, AND RISK

Let us suppose a fire manager must decide "Do I try this prescribed burn today?" The objective of the burn might be to expose mineral soil and reduce fuels. This treatment requires the **fire state** to burn within specific limits defined by the fire prescription. The manager must decide "yes" (to burn) or "no" (not to burn). In either case, there are two possible events (outcomes or results), depending on fuels and environmental conditions: (1) the fire might burn in a state, b, to accomplish his management goal or (2) it might not burn, $\not b$, in that state.

Many decision problems can be reduced (or combined) to just two responses (decision alternatives) and two events (or outcomes). The manager's task is to decide, Y or N, on the basis of uncertain evidence, n, whether his objective will obtain, b, or not obtain, $\not b$. For example, there are four possible outcomes: the conjunction (Y,b) is a "correct acceptance" or a "hit" and its complement (N,b) is a "false rejection" or a "miss"; the conjunction $(N,\not b)$ is a "correct rejection" and its complement $(Y,\not b)$ is a "false acceptance" or a "false alarm." In decision theory, the two conjunctions (N,b) and $(Y,\not b)$ are called errors of the first kind and errors of the second kind, respectively; the first is a missed detection (rejecting a true hypothesis), the second is a false alarm (accepting a false hypothesis) (see table 1).

His knowledge being imperfect, the manager's goal is to make a decision with the highest probability of achieving his objective. The manager cannot be criticized for a "bad" result of such rational decision. In the real world of imperfect knowledge, a non-zero probability exists that a good decision may have a bad result and, conversely, a bad decision may have a good result.

The performance of an observer (the fire manager) in a single decision trial is assessed in terms of the probabilities of a correct decision, $P(C)$ and error $P(E)$:

$$P(C) = P(Y,b) + P(N,\not b)$$

$$P(E) = P(Y,\not b) + P(N,b)$$

where, for example, $P(Y,b)$ is called the **joint probability**, that is, the probability that the event, b, and the response, Y, both occur on the same trial.

Objective, Goal, Function, Rule

We now divide the decision process into a logical sequence: first, the manager-observer predetermines an explicit management **objective** and a specific decision **goal**: from the goal a decision **function** is defined, which value depends on the decision of the observer; in turn, a **decision rule** is determined that maximizes (or minimizes) the decision function. For example,

— the objective might be to burn a fire in the state, b,

— the goal might be to have the largest probability of a correct decision,

— then the decision function is $P(C)$ as shown above,

— the decision rule is then, to "say YES" if the posterior probabilities (determined by the observations and prior probabilities) favor maximizing the decision function, $\max P(C)$.

Examples of classical decision goals include:

1. The resource manager may wish to simply maximize the probability of a correct decision, $\max P(C)$, as indicated above.

2. In cases with significant values at risk, the manager may wish to maximize the expected value (or minimize risk).

Table 1—Event-response conjunctions, A, and conditional probabilities, B

A.	Response		B.	Response	
Event	Y	N	Event	Y	N
b	(Y,b) "hit"	(N,b) "miss"	b	$P(Y\|b)$ "hit rate"	$P(N\|b)$ "miss rate"
$\not b$	$(Y,\not b)$ "false alarm"	$(N,\not b)$ "correct reject"	$\not b$	$P(Y\|\not b)$ "false alarm rate"	$P(N\|\not b)$ "reject rate"

3. An observer may wish to minimize the maximum probable error rate, the "minimax observer"; this case is of particular interest when the max$P$(C) observer has unknown (or very uncertain) prior probabilities.

4. Other examples of decision goal optimization are contained in the literature; most are variations of these examples. (A fire department might fix a given, tolerable false alarm rate and then work to minimize the rate of missed fire detections; this is the goal of the classical Neyman-Pearson observer, for example.) We will confine our discussion to the above three examples for illustration.

In classical discussion, probabilities are interpreted in a frequency sense; in an indefinite number of observations, an event could be expected to occur in some explicit fraction of the repetitions. But probability is commonly used in another, subjective sense (Larson 1969); for example, "The probability is 10 percent that it will rain tomorrow," or "The chances are 8 to 2 that the fire intensity will be between 3,000 and 5,000 Btu/s·ft^2." These latter examples of subjective probabilities measure an individual's "degree of belief" in a proposition (Savage 1954). That expert opinion (the result of experience) should be expressed in terms of subjective (or personal) probabilities is an implicit tenet of the Bayesian approach to decision theory (Slovic and Lichenstein 1971).

The so-called prior probabilities, $P(b)$ and $P(\not b)$, concern the relative frequency of occurrence of the respective events and are usually estimated from historical data. The prior historical occurrence of any distribution of fire states must certainly vary from locality to locality and the effect is neglected in current application. Data sources (other than personal experience) might include documented fire histories and climatologic records, for example. Some authors emphasize the admissibility of uncertainty and "subjective degrees of belief" in the prior probabilities and advise the choice of prior probabilities with large variance if one is less certain. One should always use the best information available. In a specific decision context, prior probability data is assumed to be fixed (constant and unalterable for that decision) and the occurrence, b or $\not b$, on any given trial is independent of what may have happened on any previous trial.

In addition to prior knowledge, the rational manager also makes observations of the current situation and incorporates this (imperfect) knowledge into his decision. The observer first estimates the likelihood for good or bad outcome based on skillful evaluation of the observations, n, alone. The observations, n, (in future models) might include an exhaustive list of all known physical variables affecting fire behavior such as fuels, topography, and weather; of course, any prediction, Y or N, will still have some chance of being incorrect. In this process, the rational decision maker uses a **fire model**, either systematically, as in equation 1, or intuitively, to calculate the likelihood rates at which the observations alone favor each of the four event/response conjunctions (table 1). Then the decision is made by comparing the possible outcomes with the prior odds of the current application (if they are known).

The "hit" rate, $P(\mathrm{Y}|b)$, is the conditional probability of a response "yes" given the event, b, would occur; and similarly for the other conditional probabilities (table 1).

Note that $P(\mathrm{Y},b)$ is the probability of a "hit" and $P(\mathrm{Y}|b)$ is the "hit rate." The joint probabilities of each possible outcome are as follows:

$P(\mathrm{Y},b) = P(\mathrm{Y}|b)\,P(b)$ correct acceptance, "hit"

$P(\mathrm{N},b) = P(\mathrm{N}|b)\,P(b)$ incorrect rejection, "miss"

$P(\mathrm{N},\not b) = P(\mathrm{N}|\not b)\,P(\not b)$ correct rejection, "reject"

$P(\mathrm{Y},\not b) = P(\mathrm{Y}|\not b)\,P(\not b)$ incorrect acceptance, "false alarm."

and

$$P(\mathrm{C}) = P(\mathrm{Y}|b)P(b) + P(\mathrm{N}|\not b)P(\not b) \quad (2)$$

$$P(\mathrm{E}) = P(\mathrm{N}|b)P(b) + P(\mathrm{Y}|\not b)P(\not b). \quad (3)$$

It also follows that:

$$P(\mathrm{Y},b) + P(\mathrm{N},b) + P(\mathrm{Y},\not b) + P(\mathrm{N},\not b) = 1.0 \quad (4)$$

$$P(b) + P(\not b) = 1.0 \quad (5)$$

$$P(\mathrm{Y}|b) + P(\mathrm{N}|b) = 1.0 \quad (6)$$

$$P(\mathrm{Y}|\not b) + P(\mathrm{N}|\not b) = 1.0. \quad (7)$$

The foregoing equations are a result of how the decision situation is set up and the algebra of probabilities. For example, equation 5 says (or implies) that the fire will accomplish the objective, b, or it will not; there is no middle ground or alternative. Equations 6 and 7 say that I must make a decision; for example, if I refuse to make a decision (after I have accepted the objective), then one of either Y or N must occur by default. Equation 4 says that one of the results (event/responses) of table 1 must occur, and taken with equations 2 and 3, my decision will be right or wrong!

In the interest of generality, we note that most decision problems can be reduced to the two-event, two-response situation. To illustrate, a certain fire treatment may require a residence time, b_1, flame lengths not to exceed, b_2, etc.,$\ldots b_k$; this series of specifications may be summarized in a single prescription, $\mathbf{b}_x$, which is the simple conjunction of the individual requirements:

$$\mathbf{b}_x = (b_1,\ b_2,\ \ldots,\ b_k)$$

Similarly, observational data on fuels, n_f, meteorology, n_m, and topography, n_t, will be represented by the conjunction:

$$\mathbf{n}_x = (n_f, n_m, n_t,\ \ldots)$$

and furthermore, the joint probability that $\mathbf{b}_x$ and $\mathbf{n}_x$ occur is given by

$$P(\mathbf{b}_x,\mathbf{n}_x) = P(b_1,b_2,b_3,\ldots,b_k|n_f,n_m,n_t,\ldots)\,P(n_f,n_m,n_t,\ldots)$$
$$= P(\mathbf{b}_x|\mathbf{n}_x)P(\mathbf{n}_x).$$

The premise of the formal decision procedure is that the vector, $\mathbf{b}_x$, contains sufficient and necessary information to best define the management objective and that the vector, $\mathbf{n}_x$, be a proper decision discriminator.

The so-called posterior conditional probability, $P(\mathbf{b}_x|\mathbf{n}_x)$ (hereafter written $P(b|n)$) is **the single most important probability** for the decision maker. Many "old firehorses" are respected because of their skill at estimating prior probability (from previous experience) combined with estimating (most often by subjective intuition) the probability that a result will occur, given the current observations, and also for the courage to act despite risk. The following development describes a procedure to systematically optimize this decision process.

The Bayesian model (variously called Bayes rule, theorem or function, after the Reverend Thomas Bayes, ca. 1763) states that

$$P(b_i|n) = \frac{P(n|b_i)P(b_i)}{\sum_j (P(n|b_j)P(b_j))} = \frac{P(n|b_i)P(b_i)}{P(n)} \quad (8)$$

provided that the b_j are mutually exclusive and exhaustive. $P(b_i|n)$ is the posterior probability that b_i is true, taking into account the new data, n, and the prior probability, $P(b_i)$; that is, $P(b_i|n)$ is a function of b_i with the "given" parameter set to n. $P(n|b_i)$ is the conditional probability that n would be observed when we assume b_i is known; that is, $P(n|b_i)$ is a function of n with the "given" parameter set to b_i. (Because n is a continuous function of the fuel bed parameters, these probabilities are known rigorously as probability densities. This distinction is not germane to this discussion, so we will maintain the notation, P, etc., for simplicity. Bayes theorem is succinctly discussed by Hahn and Shapiro [1967].) This latter distribution, $P(n|b_i)$, thus models the current physical conditions independent of the prior occurrence of b_i, and should be more universally applicable. $P(n|b_i)$ is determined from previous observational experience or from independent experimental research as demonstrated in the example. It is sufficient here to note the following identities:

$$P(n,b) + P(n,\not b) = P(n) \quad (9)$$

$$P(b|n) + P(\not b|n) = 1.0 \quad (10)$$

or

$$P(\not b|n) = 1 - P(b|n), \text{ etc.} \quad (11)$$

It is convenient to form the ratio of equation 8 with respect to the two states b and $\not b$ (in order that the dependence on the frequency distribution of observations, $P(n)$, be removed); b and $\not b$ are two arbitrary, mutually exclusive and exhaustive fire states, namely, those that will burn within some fire prescription and those that will not, respectively. Then

$$\frac{P(b|n)}{P(\not b|n)} = \frac{P(n|b)}{P(n|\not b)} \times \frac{P(b)}{P(\not b)}. \quad (12)$$

The left-hand side of equation 12 is the ratio of posterior probabilities (conditional on the observations, n) and gives the odds that the fire will burn in the state b. Henceforth, "odds" will specifically mean a ratio of probabilities whereby odds may assume values greater than 1.

The right-hand side of equation 12 shows explicitly that two types of information enter into the calculation of the posterior odds. The second term on the right, the ratio of prior probabilities, summarizes the observer's imperfect knowledge about the relative frequency of occurrence (odds of b vs. $\not b$) before the evidence, n, was observed, as before.

The first ratio on the right of equation 12 is

$$L(n) = \frac{P(n|b)}{P(n|\not b)}. \quad (13)$$

$L(n)$ is called the **likelihood ratio** and gives the likelihood (odds) of observing the evidence, n, on a b trial relative to observing the same evidence on a $\not b$ trial; $L(n)$ contains exclusively the information provided by the universal fire model. It is implicit that the evidence, n, is "good" data and that it is appropriate to the decision process to the degree that it makes the likelihood ratio a good decision discriminator. In the example (fig. 2A), Wilson's experimental results are transformed to remove the dependence on his prior experimental design and are presented as likelihood ratios; the likelihood ratios for the $\not b$ states shown in figure 2B are the respective inverses of the b state ratios as a consequence of equation 13. The functions $L(n)$ for the individual fire states are shown to be monotonic continuous functions of the parameter, n, and thus suitable discriminators for decision criteria. Note again that the prior odds of achieving a certain fire state (or fire prescription) will change from place to place (and time to time), but lack the benefit of specific information, n, while the likelihood ratio responds only to the current physical conditions, n, in the same manner for any given place or time.

The Max$P$(C) Observer

The objective is to burn a fire in the state b. The goal of the max$P$(C) observer is to have the maximum probability of a correct decision; cost and reward values are not involved. But the probability estimate of a correct decision depends on the current observations of the physical fire environment **and** the prior frequency distribution of the fire states in the given local situation.

As already shown, most basic decisions may be reduced to just two events, b and $\not b$, and two responses, Y and N, with the resulting four event-response conjunctions. On each trial, the observer's decision is based on the specific evidence, n. We assume that the observer has calculated (subjectively or otherwise) the prior probabilities and the likelihood ratio of the evidence, n. Thus, the maximum P(C) observer knows the posterior odds, $P(b|n)/P(\not b|n)$, of the event, b, etc.

With reference to table 1, clearly the "correct" conjunctions (Y,b) and (N,$\not b$) are preferred by the maximum P(C) observer, that is, we wish to maximize the decision function (equation 2):

$$P(\text{C}) = P(\text{Y}|b)P(b) + P(\text{N}|\not b)P(\not b).$$

Following the development above, this observer's decision rule is to say "yes" if the posterior odds favor the event b; otherwise, say "no." Thus, he should say "yes" if

$$\frac{P(b|n)}{P(\not b|n)} > 1$$

or by rearrangement, using equations 12 and 13, we have the **Max$P$(C) decision rule**:

if $L(n) > \frac{P(\not b)}{P(b)}$, say "yes," otherwise say "no."

No larger P(C) can be realized by an observer who adopts any other decision rule. This criterion also minimizes the error probability of equation 3.

Suppose a manager wishes to burn a fire in the state b_2 and in the present local situation (known to be poor burning conditions by prior experience), the prior odds suggest that b_2 is unlikely, say $P(b_2) = 1/3$, inferring a threshold value of $L(n)$:

$$L(n_0) = \frac{P(\not b_2)}{P(b_2)} = \frac{2/3}{1/3} = 2.0$$

as shown in figure 2A. Then, if the observation, n (based on fuel moisture or fuel loading) exceeds $n_0 = 5.15$, he proceeds with the prescribed burn. Note that if $P(b_2)$ is more likely, the threshold, $L(n_0)$ is smaller and he may try the burn at lower n, that is, higher fuel moisture or lighter fuel load; and conversely, for more unlikely $P(b_2)$. Thus, a rational format is suggested whereby a universally applicable fire model is appropriately adaptable to any local situation!

The Expected Value Observer

The manager faced with a decision involving major values at risk (the risk of large costs or potentially large benefits) will have at hand all relevant information to estimate a payoff matrix associated with the net value of each conjunction as shown in table 2. This observer also has information to estimate the posterior odds, etc. We construct two decision functions dependent on the evidence, n, and the respective responses, "yes" and "no":

1. The expected value, $E(V|n,\mathrm{Y})$, if the observer says "yes," and
2. The expected value, $E(V|n,\mathrm{N})$, if the observer says "no."

The two values of the payoff matrix associated with the "yes" response are weighted by the appropriate posterior probability rate

$$E(V|n,\mathrm{Y}) = P(b|n)V_{\mathrm{Y},b} + P(\not b|n)V_{\mathrm{Y},\not b}. \tag{14}$$

Similarly, for the response "no"

$$E(V|n,\mathrm{N}) = P(b|n)V_{\mathrm{N},b} + P(\not b|n)V_{\mathrm{N},\not b}. \tag{15}$$

Then, clearly, the observer should say "yes" if the expected value of the "yes" response is greater than the expected value of the "no" response, that is,

if $E(V|n,\mathrm{Y}) > E(V|n,\mathrm{N})$ say "yes," otherwise say "no."

From equations 14 and 15, this rule is expressed in terms of the posterior odds:

$$\text{If } \frac{P(b|n)}{P(\not b|n)} > \frac{V_{\mathrm{N},\not b} - V_{\mathrm{Y},\not b}}{V_{\mathrm{Y},b} - V_{\mathrm{N},b}},$$

say "yes," otherwise say "no,"

or in terms of the likelihood ratio and prior odds, **the expected value decision rule** becomes

$$\text{If } L(n) > L(n_0) = \frac{P(\not b)}{P(b)} \cdot \frac{V_{\mathrm{N},\not b} - V_{\mathrm{Y},\not b}}{V_{\mathrm{Y},b} - V_{\mathrm{N},b}}, \tag{16}$$

say "yes," otherwise say "no."

Note that if the payoff matrix has equal values for the respective b and $\not b$ events, then the maximum expected value observer obtains the same result as the max$P$(C) observer. The second ratio on the right-hand side of equation 16 contains exclusively the values and costs involved in the decision. The numerator expresses the "yes-no" value difference (the value of being correct minus the value of error), if $\not b$ prevails; the denominator similarly if b prevails. The value ratio is an expression of the relative importance of the two events, $\not b$ and b. In many cases,

Table 2—Payoff matrix of values for event/response conjunctions

	Response	
Event	Y	N
b	$V_{\mathrm{Y},b}$ value of success	$V_{\mathrm{N},b}$ cost, missed opportunity
$\not b$	$V_{\mathrm{Y},\not b}$ cost of failure	$V_{\mathrm{N},\not b}$ savings for not trying

where explicit values are lacking, the manager assigns a numerical factor that expresses his rational judgment of the relative importance of the two events. Many rational decisions are made to proceed with a task, often against large odds, simply because the manager needs (values?) to get the job done. An example for a specific prescription window is illustrated below.

Decisions Without Prior Odds and ROC Curves

The observer may use a threshold value of the likelihood ratio as the basis of his decision, even though the prior odds are unknown, thus basing the decision on the observations alone (this is the same as assuming, for example, that $P(b) = P(\not b)$). (The detractors of the modern Bayesian theorists argue rhetorically that if the "prior" probability distributions are unknown, then this assumption is equivalent to "the equal distribution of ignorance.") Or, as in figure 2A, he may simply want the likelihood ratio of the observations to favor b over $\not b$ by 2:1 odds, etc. A given threshold, $L(n_0)$, implies a specific cutoff value, n_0, as the equivalent basis of the decision, namely, a decision rule (defined below) may require "say yes" if $n > n_0$, otherwise "say no." Furthermore, the probability distributions, $P(n|b)$ and $P(n|\not b)$, are assumed to be known as in the illustrative example. Then we can define the "miss rate" and "false alarm rate," respectively, as:

the miss rate,

$$P(\mathrm{N}|b) = P(n < n_0|b)$$

$$= \int_{-\infty}^{n_0} P(n|b)\,\mathrm{d}n = \int_{-\infty}^{n_0} \frac{P(b|n)P(n)}{P(b)}\,\mathrm{d}n \tag{17}$$

$$= 1 - \int_{n_0}^{\infty} P(n|b)\,\mathrm{d}n, \tag{17A}$$

and false alarms,

$$P(\mathrm{Y}|\not b) = P(n > n_0|\not b)$$

$$= \int_{n_0}^{\infty} P(n|\not b)\,\mathrm{d}n = \int_{n_0}^{\infty} \frac{P(\not b|n)P(n)}{P(\not b)}\,\mathrm{d}n. \tag{18}$$

Thus, the mechanics for calculating the error rates associated with the observational model are specified. Note also

that the other two conditional probabilities for the truth (table 1B) are determined by use of equations 6 and 7. Then the two error rates are plotted parametrically over the domain of $n_0(-\infty < n_0 < \infty)$ as in figure 3B. (Such plots are called receiver operating characteristic (ROC) curves and were first developed by electronic engineers working on search and detection systems during the 1940's and 1950's, thus accounting for much of the terminology: "false alarm," "missed detection," etc.) The "miss" error conditional probability, $P(\mathrm{N}|b)$ is plotted on the ordinate and the "false alarm," $P(\mathrm{Y}|\not b)$, is plotted as the abscissa. The operating curve thus generated is characteristic of the observation system, namely, it is dependent only on the distribution, $P(n|b)$; note that these error rates are independent of the prior probabilities because we assumed a decision rule based only on a critical value of the observations, n_0.

It is instructive to evaluate the derivative of the miss rate with respect to the false alarm rate at the cutoff, n_0; from equations 17A and 18, we have:

$$\left.\frac{\mathrm{d}\,P(\mathrm{N}|b)}{\mathrm{d}\,P(\mathrm{Y}|\not b)}\right|_{n_0} = \frac{-P(n_0|b)}{P(n_0|\not b)} = -L(n_0). \tag{19}$$

Thus, the slope at a point on the error operating curve is equal to the negative of the likelihood ratio, $L(n)$, for the n value associated with that point, recognizing that n_0 is simply a parameter of the foregoing construction. Any decision maker who chooses an operating point on the system's ROC curve is called a "Likelihood Ratio Observer" irrespective of which decision goal he uses to fix the operating point, $L(n_0)$, on the ROC curve.

Let us consider, momentarily, the observer whose goal is simply that the hit rate should equal the false alarm rate, that is, he wants to pick a Y-N cutoff, n_0, such that when he says "yes" he has a successful burn, b, at least as often as he says "yes" and fails, $\not b$. The limiting worst case,

$$P(\mathrm{Y}|b) = P(\mathrm{Y}|\not b),$$

is shown in figure 3A as the straight line diagonal between the points (0,1) and (1,0). This observer is primarily concerned with the results when his answer is "yes," so consider the sum of joint probabilities:

$$\begin{aligned} P(\mathrm{Y}) &= P(\mathrm{Y},b) + P(\mathrm{Y},\not b) \\ &= P(\mathrm{Y}|b)P(b) + P(\mathrm{Y}|\not b)P(\not b). \end{aligned}$$

Impose the limiting condition, $P(\mathrm{Y}|b) = P(\mathrm{Y}|\not b)$, then because $P(b) + P(\not b) = 1$, it follows that

$$P(\mathrm{Y}) = P(\mathrm{Y}|b) = P(\mathrm{Y}|\not b) \tag{20}$$

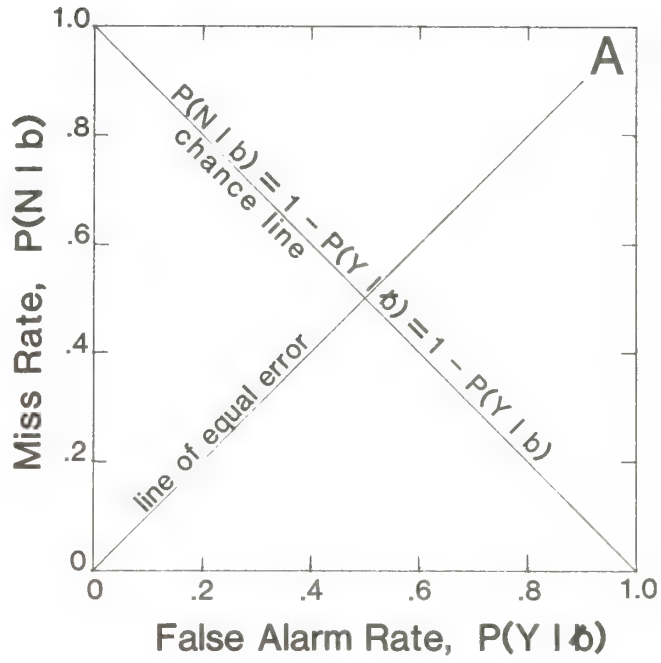
which means that this observer's objective is achieved whenever the probability of a "yes" response is the same when either condition b or $\not b$ occurs, that is, he leaves the choice to chance and achieves his objective. The negative diagonal in figure 3A, (0,1) to (1,0), is called the "chance line." The probability of error for this observer is

$$\begin{aligned} P(\mathrm{E}) &= P(\mathrm{N},b) + P(\mathrm{Y},\not b) \\ &= P(\mathrm{N}|b)P(b) + P(\mathrm{Y}|\not b)P(\not b) \text{ as before.} \end{aligned}$$

Applying equation 20 and the usual identities and rearranging terms, we have

$$P(\mathrm{E}) = P(b)(1 - 2P(\mathrm{Y})) + P(\mathrm{Y}) \tag{21}$$

from which we see that:



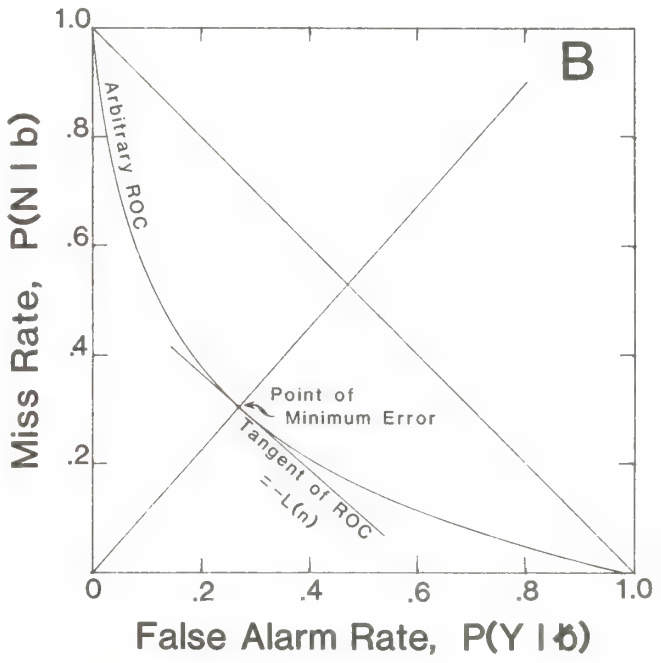


Figure 3—Receiver operating characteristic (ROC) example plot.

1. If the state b is certain, $P(b) = 1$, then the probability of error, $P(\mathrm{E}) = (1 - P(\mathrm{Y})) = P(\mathrm{N})$.

2. Alternately, if $\not b$ is certain, $P(b) = 0$, then $P(\mathrm{E}) = P(\mathrm{Y})$.

3. Most importantly, if $P(\mathrm{Y}) = 0.5$ (if the response "yes" is determined by the flip of a fair coin, $P(\mathrm{Y}) = P(\mathrm{N}) = 0.5$), then this observer's error rate is independent of the prior probabilities, $P(b)$ or $P(\not b)$ as in equation 21;

furthermore, all entries in the 2×2 matrix (table 1B) of conditional probabilities are equal,

$$P(\mathrm{Y}|b) = P(\mathrm{Y}|\not b) = P(\mathrm{N}|b) = P(\mathrm{N}|\not b) = 0.5, \text{ and}$$

the observer is operating at the (0.5,0.5) point on the ROC chance line. At this point, (0.5,0.5) in figure 3A, the operating curve perpendicularly intersects the line of equal errors and the maximum probable error is a minimum; note that this is the point on the chance operating curve that lies closest to the ROC origin, the origin being the point of zero error. Furthermore, if the observer biases his coin so that the probabilities of "yes" and "no" are unequal, then the operating point (the 2×2 matrix of conditional probabilities) moves away from (0.5,0.5) along the chance line resulting in an increase in the maximum probable error rate.

A decision system's performance is judged by the location of its operating curve. Good performance is measured in the space below the chance line by how close the operating curve approaches the origin, indicating low error rates. It is possible for a decision system to operate in the space above the chance line by using bad decision rules or bad observational data. "Bad information is worse than no information." The manager-observer should learn to recognize such cases, where he is better off flipping a fair coin than using bad information.

The Minimax Observer

Recalling that "good" operating curves occupy the space below the chance line, and are thus convex downward, where either error rate should be monotonically decreasing as the other increases as in the example (figure 3B), we can suggest a decision rule that **minimizes the maximum probable error rate**, independent of any knowledge of prior probabilities. By geometric inspection of figure 3B, one may determine the point of closest approach of an operating curve (analytic or otherwise) to the origin. The shortest line segment from the origin to a point on the operating curve is perpendicular to the tangent, $-L(n_0)$, at that point. Even for imperfect and empirically derived operating curves that point will be more or less close to the intersection with the line of equal error rates.

Our goal, again, is to minimize the probability of error. Setting the derivative of $P(\mathrm{E})$ with respect to the false alarm rate, $P(\mathrm{Y}|\not b)$, equal to zero gives a minimum and not a maximum because $-L(n)$ is an increasing function of the abscissa, $P(\mathrm{Y}|\not b)$ (equation 3):

$$P(\mathrm{E}) = P(\mathrm{Y}|\not b)P(\not b) + P(\mathrm{N}|b)P(b)$$

$$\frac{\mathrm{d}\,P(\mathrm{E})}{\mathrm{d}\,P(\mathrm{Y}|\not b)} = 0$$

$$= P(\not b) + \frac{\mathrm{d}\,P(\mathrm{N}|b)}{\mathrm{d}\,P(\mathrm{Y}|\not b)}\,P(b)$$

then again, by equation 19, we have

$$\frac{\mathrm{d}\,P(\mathrm{N}|b)}{\mathrm{d}\,P(\mathrm{Y}|\not b)} = -L(n_0) = -\frac{P(\not b)}{P(b)}.$$

Thus, $L(n_0) = P(\not b)/P(b)$, as before, but here we have demonstrated that the point (false alarm rate, miss rate) at which the slope of the operating curve is $-L(n_0)$, is the operating point where the maximum probable error is a minimum; that is, the maximum probable error over all n but a minimum over all possible $P(\mathrm{Y}|\not b)$ and similarly for $P(\mathrm{N}|b)$.

The ROC is a known characteristic of the observation/prediction model. To operate with minimum error rate, the observer should use **the minimax decision rule**: if $L(n) > L(n_0)$, say "yes," otherwise say "no," where $L(n)$ is the result of observation as before and where $-L(n_0)$ is equal to the slope of the ROC curve at the point of closest approach to the origin; for the minimax observer $L(n_0)$ tends to be more or less close to the line of equal errors (where $L(n_0) = 1$), depending on the precise shape of the ROC at the point of minimum error (note that this observer's goal is to minimize the **error rate** and not the total error as the max$P(\mathrm{C})$ observer above).

An irrational observer could include in his decision rule a few values of n for which corresponding values of $L(n)$ are less than some of those not included in his rule; so, he responds Y to those observations of n that represent less evidence for b than for other good observations to which he responds N. Such an observer is not a likelihood ratio observer! Inescapably, he is still working within the ROC plot, somewhere in the space above the system's ROC curve. It must be emphasized that, for any given false alarm rate, the miss rate cannot be made smaller than that for the **likelihood ratio observer**. (Similarly, for any given miss rate, the false alarm rate cannot be smaller.) Note, however, that the error rates may all vary with the decision rule at the option of the observer.

A city fire department chooses a very low fire detection threshold to reduce errors of the first kind (missed detections) and hence must tolerate many false alarms; alternatively, a forester may pass up several missed opportunities because he cannot risk a bad burn. In both instances, the managers are not acting as minimax observers to minimize total error, but must consider the values and prior probabilities as in the previous examples above. Both are considered good likelihood ratio observers if they choose an operating point ($L(n)$) on their ROC curve.

Prescription Windows

While developing error equations 17 and 18, we assumed a Y/N cutoff in terms of n_0 (not $L(n_0)$) because the arithmetic was easier; $L(n)$ is an equivalent discriminator because it is always a piecewise monotone function of n. $L(n)$ is the more practical in many applications; for example, the likelihood ratio for $b_z = (b_1, \not b_2)$ in the example is calculated, following equation 13:

$$L(n) = \frac{P(n|b_z)}{P(n|\not b_z)},$$

as shown in figure 4A. The decision threshold in b_z is specified by a single value of the odds, $L(n_0)$, whereas to accomplish the same purpose, two very complicated critical values of n would be required: a cuton value, $n_{0,1}$ **near** the b_1 limit, and cutoff value, $n_{0,2}$ **near** the $\not b_2$ limit.

In figure 4B, the likelihood ratios are plotted also for the burning windows $(b_1, \not b_3)$ and $(b_2, \not b_3)$, respectively, the fractions of fireline aflame between 0.01 to 0.99 and between 0.5 to 0.99. Note that the manager might improve

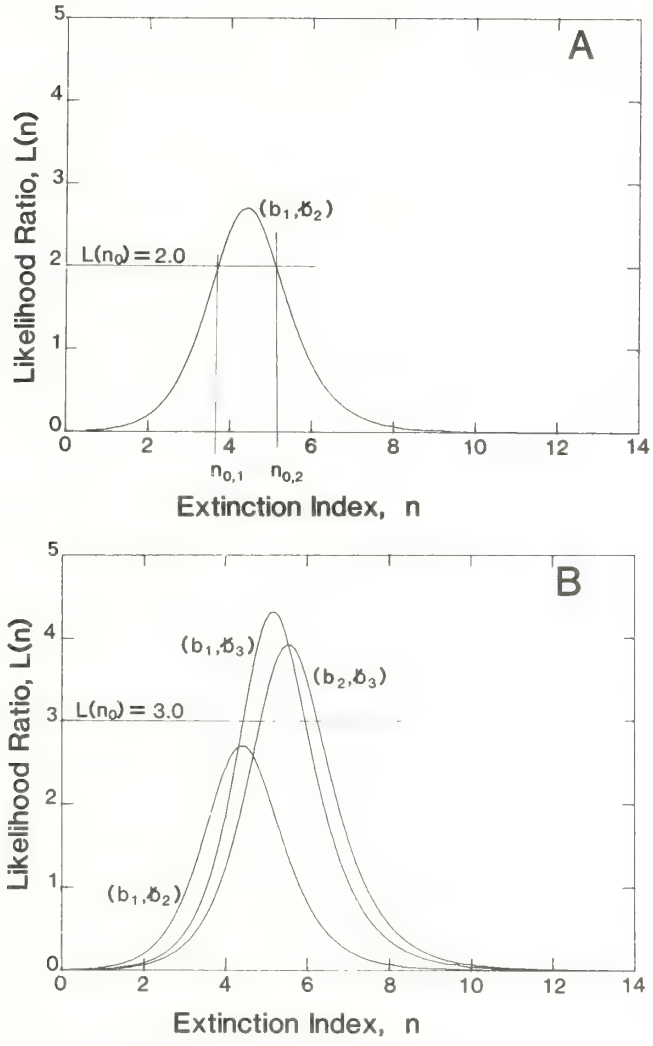


Figure 4—Likelihood ratios for conjunctions of fire states (prescription windows).

the likelihood (odds) of hitting his burning window (by observing a value of n) if the window is wider as in the former case, or the window is moved to better burning conditions as in the latter case. Similarly, if he knows that his prior odds are, say, 3:1 against the prescription $(b_1,\not b_2)$, that is, $L(n_0) = 3$, then he cannot rationally expect to hit that prescription; whereas, by widening the window (as in $b_1,\not b_3$) two effects improve his chances: first, $L(n)$ will improve as in figure 4B, and secondly, the prior odds against $(b_1,\not b_3)$ are expected to be smaller, that is, $L(n_0) < 3$, because, again the historical record will show more fires in $(b_1,\not b_3)$ than in $(b_1,\not b_2)$.

Suppose, now, a manager has an economically important fire treatment to perform; the fire prescription is $(b_1,\not b_2)$ as above with the same prior odds, $P(\not b)/P(b) = 3$. As an expected value observer, the manager has considered all of the relevant treatment costs and benefits to construct a payoff matrix with the following components:

- If the burn is successful, the net present value would be $V_{Y,b}$ = \$30 per acre. In this simple example, net value is composed of a depreciated future benefit of \$50/acre, less \$10/acre fixed planning and preparation costs and \$10/acre for labor and supplies.
- The missed opportunity value, $V_{N,b}$ = −\$15/acre, includes the \$10/acre fixed cost and \$5/acre associated with the lost opportunity and delayed burning schedule.
- The cost to try and fail, $V_{Y,\not b}$ = −\$25/acre, is composed of \$10/acre fixed cost, \$10/acre labor and supply, and \$5/acre loss to present net value due to site damage.
- And, the value of correctly deciding not to burn, $V_{N,\not b}$ = −\$10/acre, is just the planning fixed cost.

Then the decision threshold, $L(n_0)$, becomes (by equation 16),

$$L(n_0) = \frac{P(\not b)}{P(b)} \cdot \frac{V_{N,\not b} - V_{Y,\not b}}{V_{Y,b} - V_{N,b}}$$

$$= 3 \cdot \frac{(-10) - (-25)}{(30) - (-15)} = 3 \cdot \frac{1}{3} = 1.0.$$

Thus, the effect is to lower the decision threshold, $L(n_0)$, which is readily justified by the expected payoff. Note that the "fixed planning cost" has no resultant effect on the decision function, basically because that cost was incurred (by some previous decision) before we arrived at this decision point and is an obligation regardless of the decision. Also note that generally (not always), the two errors will have less value than their respective correct conjunctions, thus both numerator and denominator of the value ratio (eq. 16) will have positive values. (An exercise for the reader is to consider the dilemma of the manager who "must decide between the lesser of two evils.") In many practical examples, $V_{Y,b}$ will be the dominant positive value; hence the value ratio will have a positive value, less than 1, so the payoff justifies a decision that might otherwise be against the prior odds.

Of course the cost and benefit values in the value ratio are associated with the specific prescription, $b = (b_1,\not b_2)$, for example. The manager may consider the tradeoffs of adjusting the prescription window and the corresponding value ratios to arrive at the best possible decision.

If we vary the decision rule to successively enlarge the range of acceptable n, we will start with a large $L(n_0)$ (fig. 4) at the ROC point (0,1) where the acceptable range is zero and (by **any** rational decision rule) we will always say "no" where we will never have a false alarm, where the miss **rate** equals 1.0, and the (joint) probability of a missed opportunity is equal to the (prior) probability of the opportunity. And we will end with a small $L(n_0)$ at the ROC point (1,0) where we always say "yes," never miss an opportunity, but the false alarm rate equals 1.0 and the (joint) probability of a false alarm is equal to the (prior) probability that the opportunity does not occur (refer to equations 2 to 7). Furthermore, the range of acceptable n must be nondecreasing over the entire path because the ROC slope, $-L(n)$, varies so.

Model Performance

An ROC curve is uniquely determined for each pair of distributions, $P(n|b)$, $P(n|\not b)$, and is the same for all decision rule criteria. There exists, then, a family of ROC curves that depend on the parameter, b; which family is represented by the fire states, b_1, b_2, b_3.

The ROC plot for Wilson's model is shown in figure 5A. The continuous curves are generated by equations 17 and 18, and the respective curves in figure 1. The data points are the appropriate experimental counts of burns, b, and not-burns, $\not b$, in sequential increments of the parameter n of equation 1. The extinction index, n, of equation 1 is the independent variable of the parametric ROC plot for each member of the family, b_i (i = 1,2,3). Each curve begins with $n=0$ near the ROC point (1,0) and ends near (0,1) with $n>14$.

Neglecting the parameter, n, there is no significant difference in the ROC family of curves. The utility of the model is demonstrated by the low values of the points of minimum error rate: (0.12,0.12), (0.13,0.13), and (0.15,0.15), respectively for b_1, b_2, and b_3. But these points occur when the parameter, n, equals 4.25, 4.62, and 5.75, respectively, demonstrating that each fire state will have its own individual ROC.

The data points for b_1 at low n in figure 5A depart significantly from the ideal. This variance has roots in the physical observation process. The large miss error is because several fires burned that should not have been expected to burn; the low n indicates poor burning conditions, the state b_1 being fires that did not go out. By equation 1 these were fuel beds with light loading and/or high moisture content. It was noted during the experiment that a few of these fires could be sustained by two or three individual fuel sticks that may have had anomalously high heat of combustion (pitch and resins) or low moisture. In other fires with very light loading, the intersection of three or more sticks constituted a "jackpot" with significantly hotter fire behavior. The spatial distribution of these jackpots could not be controlled, even with extreme experimental precaution, to preclude some of the fires being sustained by jackpot-to-jackpot propagation, and which would have been predicted to go out if the fuel bed had been perfectly homogeneous. These inhomogeneities are insignificant in heavier loaded fuel beds, larger n, or do not affect our expectations for the hotter burning states. Thus there are two points to make:

1. Inhomogeneity is a physical variable that is not "recognized" in the fire model, is not incorporated in the likelihood ratios, nor in the ROC's, etc. It is, however, a parameter whose statistics could vary from one locality to another and so affect the prior odds on which the manager bases his decision.

2. These ROC curves indicate an ideal limit of performance; they represent the best that you can expect to do with the information observed and, in some cases, even that might be difficult to achieve.

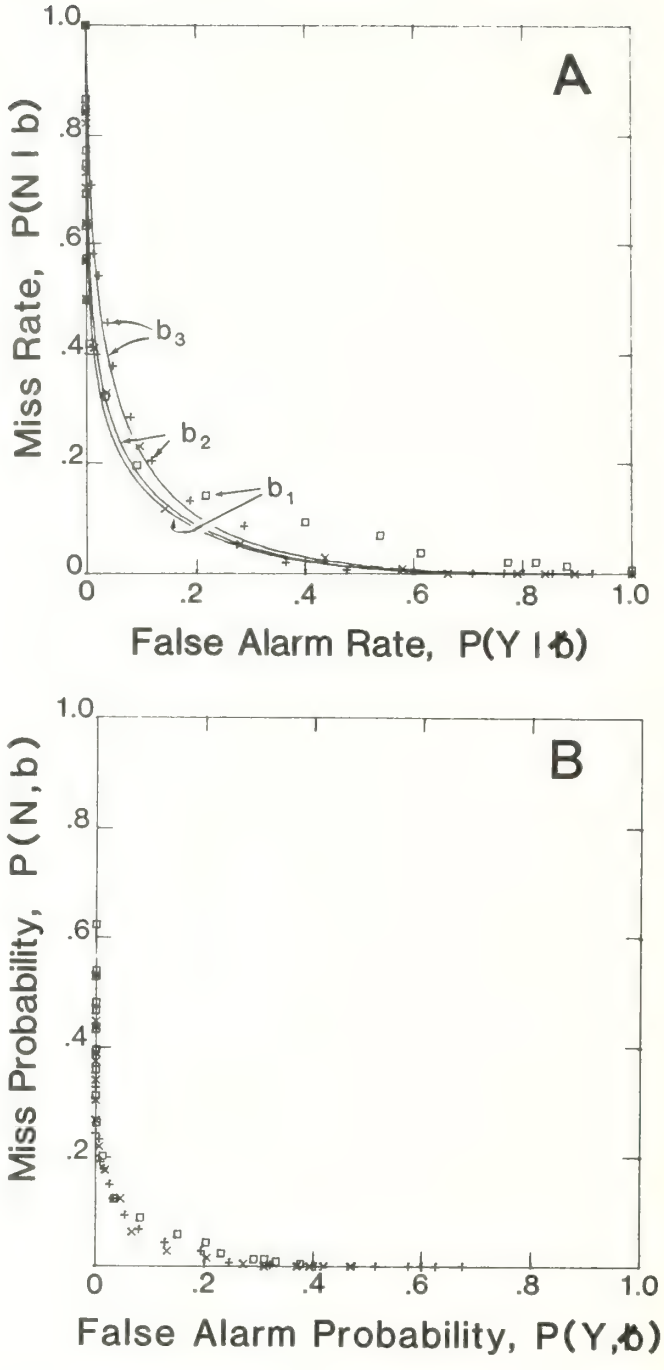


Figure 5—(A) ROC for the marginal fire states; (B) plot of posterior experimental errors where:

$P(Y,\not b) = P(Y|\not b)\,P(\not b)$ and

$P(N,b) = P(N|b)\,P(b)$.

In figure 5B the error rates are multiplied by their respective prior probabilities **of the experiment**, thus giving a plot of the expected errors for the experiment, namely, the joint probabilities. This plot is typical of what might be expected in a specific application, but of course it will vary by application because the prior probability distribution will vary substantially.

As we have noted, the distributions of marginal states, b, are bounded at the upper limit when 100 percent of the fireline is aflame. We have started a cursory examination of fire states defined in alternative terms of fire intensity without an upper bound. In particular, flame length is also a measure of intensity that shows promise of describing and discriminating between the hotter fire states. Preliminary analysis (of the 120+ "hot" fires $> b_3$) indicates a family of ROC curves that begin very close to those of figure 5A and then successively approach closer to the ROC origin as flame lengths lengthen.

CONCLUSIONS

The utility of a fire model in the decision process is greatly enhanced when a probable distribution of likely events is available to the decision maker. These distributions allow him to weigh the alternatives and risks involved, that is, to make good decisions. When a deterministic fire model gives a single value prediction, the fire manager is left wanting, with only his subjective experience as guide. How close to the true value is the prediction? What is the risk that it is wrong? Is the prediction appropriate to the local situation?

A fire model cannot be expected to respond to variations other than those observed and measured as inputs to the model. For a model to be widely useful, it should express the likelihood (as in equation 13 or in $P(n|b)$, etc.) that the currently measured physical conditions would be observed for the fixed fire state in question (or some equivalent expression). The model will, then, perform optimally, without built-in development biases and with a provision for differences between various localities (and times). A large portion of forestry literature is comprised of case studies, isolated anecdotal data, and reports of previously unobserved (rare) events. The task of compiling data bases for use of "expert systems" by decision makers must be done with such extreme care that the likelihood of any event, observation, or condition is not unreasonably overstated. Furthermore, isolated instances represent a single data point and not a distribution; hence, they are of little value to the person who must take risks when one does not know where in the distribution that data point might lie!

The next task is to develop a system for calculating ranges of fire behavior that fire managers will find useful and easily understood.

REFERENCES

Egan, James P. 1975. Signal detection theory and ROC analysis. New York: Academic Press. 277 p.

Hahn, G. J.; Shapiro, S. S. 1967. Statistical models in engineering. New York: Wiley and Sons. 355 p.

Larson, Harold J. 1969. Introduction to probability theory and statistical inference. New York: John Wiley and Sons. 387 p. (Ch. 9).

Rothermel, Richard C. 1972. A mathematical model for predicting fire spread in wildland fuels. Res. Pap. INT-115. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 40 p.

Savage, Leonard J. 1954. Foundations of statistics. New York: John Wiley and Sons. 294 p.

Slovic, Paul; Lichtenstein, Sarah. 1971. Comparison of Bayesian and regression approaches to the study of information processing and judgment. Organizational Behavior and Human Performance. 6: 649-744.

Wilson, Ralph A., Jr. 1985. Observations of extinction and marginal burning states in free burning porous fuel beds. Combustion Science and Technology. 44: 179-194.

Wilson, Ralph A., Jr. 1987. A theoretical basis for modeling probability distributions of fire behavior. Res. Pap. INT-382. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

A method is proposed for predicting a probabilistic distribution of fire behavior. A fire model gives conditional distributions of the physical fire site parameters one would observe for given fire states. The probabilistic prediction is provided by Bayes formula and knowledge of the prior distribution of fire states at specific sites. Thus, the fire model is independent of the site location. The techniques of plotting Receiver Operating Characteristics are demonstrated with examples to optimize and test the fire model's performance.

KEYWORDS: decision theory, marginal burning

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

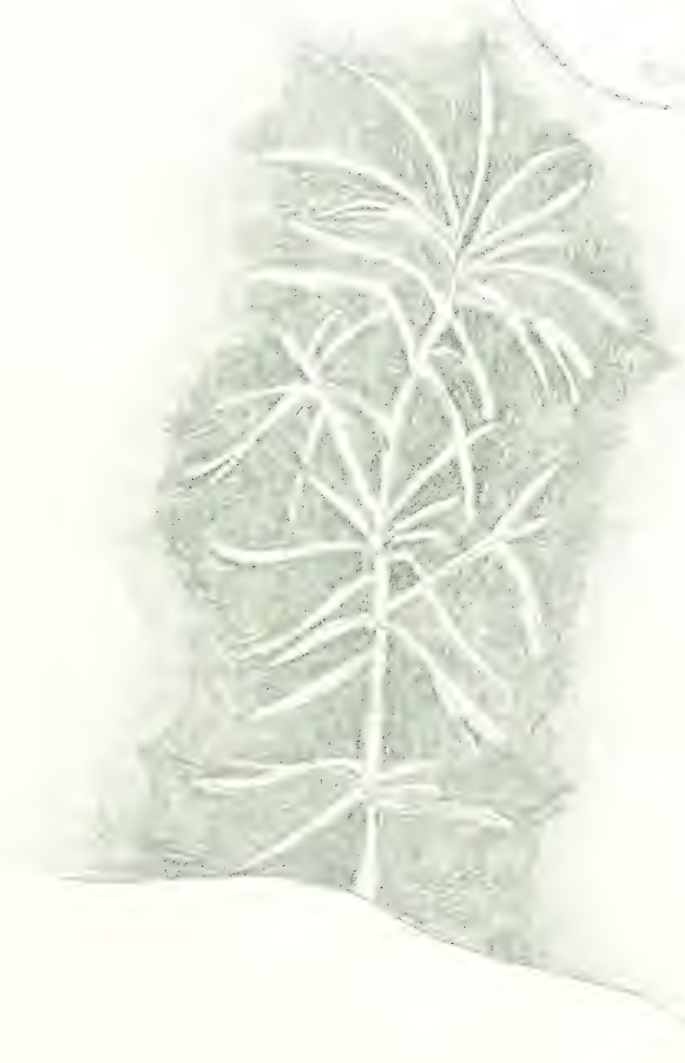
Forest Service

**Intermountain
Research Station**

Research Paper
INT-383

Occurrence of Conifer Seedlings and Their Microenvironments on Disturbed Sites in Central Idaho

Kathleen Geier-Hayes



THE AUTHOR

KATHLEEN GEIER-HAYES is a forester in the Douglas-fir and Ponderosa Pine Ecosystems research work unit located at Intermountain Station's Forestry Sciences Laboratory in Boise, ID. She has worked part-time in this work unit since 1979 and joined the Intermountain Station on a full-time basis in 1986. She earned a B.S. degree in biology at Boise State University and an M.S. degree in forest science at the University of Idaho.

RESEARCH SUMMARY

Natural regeneration of six conifer species was surveyed on three central Idaho habitat types (h.t.): Douglas-fir/white spirea h.t. (*Pseudotsuga menziesii/Spiraea betulifolia* h.t.), grand fir/mountain maple h.t. (*Abies grandis/Acer glabrum* h.t.), and grand fir/blue huckleberry h.t. (*Abies grandis/Vaccinium globulare* h.t.). The species sampled were lodgepole pine (*Pinus contorta*), western larch (*Larix occidentalis*), ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), Engelmann spruce (*Picea engelmannii*), and grand fir (*Abies grandis*). Seedling occurrence was related to seedbed, amount and kind of shade cover, site preparation method (no site preparation, broadcast burning, light and heavy scarification), and silvicultural method (clearcutting, seed-tree cutting, shelterwood cutting, selection cutting). An "index of regeneration efficiency" was developed to indicate possible beneficial and detrimental effects of seedbeds or covers for each seedling species. The indexes and percentage occurrences of seedlings are used to provide recommendations for silvicultural and site preparation treatments that can be used to obtain desired natural regeneration in the three habitat types.

September 1987
Intermountain Research Station
324 25th Street
Ogden, UT 84401

Occurrence of Conifer Seedlings and Their Microenvironments on Disturbed Sites in Central Idaho

Kathleen Geier-Hayes

INTRODUCTION

Successful forest management requires prompt tree regeneration following timber harvesting. With the increase in planting costs, many forest managers have turned to natural regeneration to restock stands (Gashwiler 1970). Natural regeneration of stands to adequate stocking levels is often slow (Fiedler and others 1985; Minore and Dubrasich 1981), and many studies have investigated the seedbed requirements for various conifer species. Few studies, however, have characterized the seedling microenvironment in terms of both seedbed and seedbed cover.

Seed germination and establishment depends on critical environmental conditions. A microenvironment that provides a seed with the requirements for germination and establishment was defined by Harper (1977) as a "safe site." The absence of a particular species from an area may be due either to insufficient seed dispersed to the site or to a lack of safe sites. Silviculturists use several methods to manipulate the amount of available conifer seed, but little is known about the required safe sites for that seed. Once identified, site preparations after timber harvesting can be manipulated to provide as many safe sites as possible for a desired conifer species. This study was undertaken to define safe sites for coniferous trees in west central Idaho.

METHODS

The study was conducted in the Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and grand fir (*Abies grandis*) forests on the Boise and Payette National Forests in west-central Idaho. In the Douglas-fir forests, Douglas-fir is the dominant species often growing with ponderosa pine (*Pinus ponderosa*) (Steele and others 1981). Grand fir is the dominant conifer in grand fir forests, often growing with ponderosa pine, lodgepole pine (*Pinus contorta*), Douglas-fir, Engelmann spruce (*Picea engelmannii*), and western larch (*Larix occidentalis*). Within these forests, three habitat types based on potential climax vegetation were sampled: Douglas-fir/white spirea (*Pseudotsuga menziesii/Spiraea betulifolia*) habitat type (h.t.), grand fir/mountain maple (*Abies grandis/Acer glabrum*) h.t., and grand fir/blue huckleberry (*Abies grandis/Vaccinium globulare*) h.t. (Steele and others 1981). The Douglas-fir habitat types are normally drier and warmer than the grand fir habitat types. The grand fir/mountain maple h.t. occurs in environments in the grand fir zone that are warmer than the grand fir/blue huckleberry h.t. environment.

Sample sites were located in the study area "subjectively but without preconceived bias" as described by Mueller-Dombois and Ellenberg (1974). Areas identified as Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry h.t. were reconnoitered to identify stands with some type of disturbance. Sample points were selected to represent the range of silvicultural methods and site preparation combinations available. The sample points were in representative portions of the stands in areas with uniform treatments. The silvicultural methods sampled included clearcuts, shelterwood cuts, seed-tree cuts, and group selection cuts. Site preparations included none (no slash disposal and little harvesting impact), broadcast burning, and two types of scarification—light scarification (from slash disposal or harvesting activities) and heavy scarification (contour terracing). Only sites with 5-year-old or older disturbances were included. At each sampling point, five 108-ft^2 (10-m^2) circular plots were located with one at the center (designated CENTER) and four peripheral (designated LEFT, RIGHT, UP, DOWN) 22.5 ft (6.9 m) from the middle of plot CENTER. Plots UP and DOWN were perpendicular to the contour upslope and downslope of CENTER respectively. Plots RIGHT and LEFT were on the contour to the right and left of CENTER. In using this sampling method, I assumed that safe sites were randomly dispersed within the uniform site treatment. All plots will be referred to as seedling plots. I treated each seedling plot as a separate plot for summarization.

For each seedling plot, I recorded the percentage of the plot covered by various soil surface conditions (seedbeds) and percentage coverages of vegetation and debris. Information on all conifer seedlings present included species, seedbed, and species of or kind of overhanging (influential) vegetation or debris. Seedbed categories were litter-covered mineral soil, bare mineral soil, moss mats, residual duff, and rotten wood. Rocks and stumps were also recorded as seedbeds.

Seedlings 3 years old or older, but younger than the disturbance, were recorded. Seedlings were clipped and aged in the laboratory, or when possible, were aged on site by counting bud scars or nodes. Each individual seedling or cluster of seedlings (cache) was recorded as an occurrence. For each sample site I recorded aspect, slope, and elevation. The dates (year) of timber harvesting and site disturbance were estimated from management records, plantation signs, tree growth release indications from increment borings, and cross sections of machine scars that occurred during timber harvesting. All sampling

occurred during the summers of 1984 and 1985. A total of 56 sites (280 seedling plots) were sampled in the Douglas-fir/white spirea h.t., 70 sites (350 seedling plots) in the grand fir/mountain maple h.t., and 24 sites (120 seedling plots) in the grand fir/blue huckleberry h.t.

The data from this study were not well suited to statistical analysis because the number of seedlings sampled of each species inadequately represented all the various silvicultural method-site preparation combinations, and the distribution of sampling plots throughout the combinations was not uniform. Rather, this was intended as a retrospective study of the effects of the various treatment combinations on the occurrence of natural tree regeneration.

I summarized the data by harvest-regeneration treatments, site preparation treatments, and amount of shade cover. For these summaries, the results are expressed as percentages based on the average number of seedlings for each treatment. Averages resulted from dividing the number of seedlings in a treatment by the number of treatments. Average number of years to establishment after disturbance were obtained by subtracting the seedling age from the disturbance age and averaging the results for each species in a habitat type. The average is a weighted average based on the number of seedlings of each species.

To evaluate the effect of the safe site components (seedbed or cover), an "index of regeneration efficiency" (RE) was calculated. The RE values were obtained by dividing the percentage occurrence of seedlings in a safe site component by the percentage occurrence of the safe site component. Percentage occurrence of seedlings is the percentage of seedlings that were found on or under a safe site component based on the total number of seedlings. Percentage occurrence of a safe site component was obtained by multiplying constancy of the safe site component (percentage occurrence over all plots) by average cover of each component. The values were totaled for all covers or seedbeds, and the totals were used to obtain percentage occurrence of a particular safe site component. The percentage occurrence of seedlings used to obtain RE values is not the same as the percentages used for the previous summaries. This is because average number of seedlings per safe site component could not be obtained since the area occupied by each component varied from plot to plot. For this reason, RE values were used for these summaries. A regeneration efficiency of 1.00 indicates that the seedlings occurred in a particular safe site component in proportion to the occurrence of the component. Indexes greater than 1.00 indicate that seedling occurrence was much higher on a particular component than the occurrence of the component, and indexes less than 1.00 indicate that seedling occurrence is much lower than the occurrence of the component. Using this index, possible beneficial or detrimental effects of the safe site can be indicated. The following subjective categories and classes were assigned to RE values:

Class 1: 0 to 0.25, very inefficient
Class 2: 0.26 to 0.75, inefficient
Class 3: 0.76 to 1.50, efficient
Class 4: 1.51 to 3.00, moderately efficient
Class 5: 3.01 and greater, very efficient.

RESULTS AND DISCUSSION

Approximately 370 seedlings per acre (920 per ha) were found in the Douglas-fir/white spirea h.t. (table 1). Regeneration was greater in the grand fir forests with 480 seedlings per acre (1,190 per ha) in both grand fir/mountain maple and grand fir/blue huckleberry h.t. Of the seedlings in the Douglas-fir/white spirea h.t., 64 percent were Douglas-fir, while ponderosa pine made up 24 percent of the total. In the grand fir forests, grand fir accounted for 49 percent in the mountain maple h.t. and 50 percent in the blue huckleberry h.t. Douglas-fir was also common. The average number of years to establishment after disturbance varied by species and by habitat type (table 1). Overall, seedling establishment took longest in the cool grand fir/blue huckleberry h.t. and was shortest in the moderate grand fir/mountain maple h.t.

Seedbeds

The most common seedbed safe site component in all three habitat types was litter-covered mineral soil followed by bare mineral soil and moss mats (table 2). Rocks or stumps, rotten wood, and residual duff were less common. Residual duff was amassments of organic material that had accumulated under the predisturbance stand and had remained intact following the disturbance. Litter-covered scarified soils were mineral soils that had been exposed during the disturbance and were accumulating litter. Moss mats were composed primarily of juniper haircap moss (*Polytrichum juniperinum*), which produces loose, erect stems and was usually found on scarified soils.

In many cases RE values were very efficient or moderately efficient for seedlings on residual duff, rotten wood, or moss mats. The RE values were mostly inefficient and efficient for seedlings on litter-covered and bare mineral soil. In other areas, investigators have found that seedlings often occurred on seedbeds of rotten wood or duff. Knapp and Smith (1982), in the Medicine Bow Mountains of southeastern Wyoming, and Day (1964), in the Crowsnest Forest of southwest Alberta, found that Engelmann spruce seedlings occurred on rotten wood and moss mats in a larger proportion than would be expected from the area occupied by the seedbed (RE value greater than 1.00). Day (1964) also found that "mineral soil with incorporated humus" and "fermented and humified humus" were very efficient seedbeds for Engelmann spruce. Harvey (1982) states that rotten wood and humus provide a more favorable seedbed than does mineral soil because mineral soil gains and loses nutrients rapidly, has low nutrient and moisture holding capacities, and changes temperature quickly, whereas humus and decayed wood gain and lose nutrients slowly, have high nutrient and water-holding capacity, and change temperature slowly. Soil organic matter such as humus and decayed wood also increase the ability of the soil to support mycorrhizae, particularly on dry slopes (Harvey and others 1976).

Table 1—Average number of tree seedlings per acre, percentage occurrence per acre, and average number of years to establishment after disturbance for tree seedlings in the Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry habitat types

Tree species	Average number of seedlings per acre	Percent of total sample	Average number of years to establishment after disturbance	Range of years to establishment
Douglas-fir/White Spirea Habitat Type				
Lodgepole pine	44	12	3	[1]0 - 14
Ponderosa pine	87	24	5	0 - 18
Douglas-fir	238	64	9	0 - 25
Total	369	100	[2]7	
Grand Fir/Mountain Maple Habitat Type				
Lodgepole pine	5	1	2	0 - 5
Western larch	21	4	1	0 - 14
Ponderosa pine	51	11	5	0 - 13
Douglas-fir	144	30	7	0 - 46
Engelmann spruce	25	5	3	0 - 6
Grand fir	234	49	7	0 - 30
Total	480	100	6	
Grand Fir/Blue Huckleberry Habitat Type				
Lodgepole pine	29	6	9	2 - 20
Ponderosa pine	38	8	11	3 - 19
Douglas-fir	90	19	8	0 - 19
Engelmann spruce	81	17	7	0 - 22
Grand fir	237	50	9	0 - 29
Total	475	100	9	

[1]0 years to establishment means that seedlings established in the same year that disturbance took place.
[2]Weighted average.

Table 2—Percentage occurrence of natural tree seedlings by seedbed with regeneration efficiencies (RE)[1] classes of seedbeds for Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry habitat types

Species	Scarified soil: Litter-cover		Scarified soil: Bare		Moss mat		Rotten wood		Residual duff		Rocks or stumps	
	Pct	*RE class*[2]	*Pct*	*RE class*	*Pct*	*RE class*	*Pct*	*RE class*	*Pct*	*RE class*	*Pct*	*RE class*
Douglas-fir/White Spirea Habitat Type												
Lodgepole pine	64	3	36	3	—	—	—	—	—	—	—	—
Ponderosa pine	38	2	47	4	13	5	2	4	—	—	—	—
Douglas-fir	63	3	29	3	6	4	1	3	1	2	—	—
Seedbed occurrence[3]	63		29		2		<1		4		<1	
Grand Fir/Mountain Maple Habitat Type												
Lodgepole pine	25	2	25	3	56	5	—	—	—	—	—	—
Western larch	17	1	49	4	28	5	6	5	—	—	—	—
Ponderosa pine	69	3	13	3	16	4	2	3	—	—	—	—
Douglas-fir	52	3	25	3	21	4	1	2	1	4	—	—
Engelmann spruce	50	2	18	3	27	5	5	4	—	—	—	—
Grand fir	65	3	14	2	18	4	2	3	1	5	—	—
Seedbed occurrence	67		22		8		2		<1		<1	
Grand Fir/Blue Huckleberry Habitat Type												
Lodgepole pine	30	2	50	5	20	4	—	—	—	—	—	—
Ponderosa pine	31	2	38	4	23	4	8	4	—	—	—	—
Douglas-fir	59	3	19	3	16	3	6	4	—	—	—	—
Engelmann spruce	46	2	3	1	45	5	3	3	3	4	—	—
Grand fir	63	3	10	2	10	3	15	5	2	3	—	—
Seedbed occurrence	67		15		13		2		2		<1	

[1]Regeneration efficiency is the percentage occurrence of the seedling species divided by the percentage occurrence of the safe site component.
[2]Class 1: 0 to 0.25, very inefficient; class 2: 0.26 to 0.75, inefficient; class 3: 0.76 to 1.50, efficient; class 4: 1.51 to 3.00, moderately efficient; class 5: 3.01 and greater, very efficient.
[3]Seedbed occurrence is the percentage occurrence of a seedbed over all microplots.

Cover

The second component of safe sites is the influence of vegetation and debris. The occurrence of different seedling species varied according to the amount of shrub canopy cover (shade) over the seedling plot (table 3). However, the trends for most species were similar between habitat types. Most seedling species occurred in moderate (33 to 66 percent shrub canopy cover) and heavy (67 to 100 percent) shade. This included even the shade-intolerant species ponderosa pine and lodgepole pine (as defined by Daniel and others 1979; Minore 1979), which were found predominately in moderate shade in all three habitat types. Douglas-fir was found most often under heavy shade. Engelmann spruce, which is rated as less shade tolerant than Douglas-fir (Minore 1979), was found most often under heavy shade in grand fir/mountain maple h.t. and under light (0 to 33 percent) shade in the grand fir/blue huckleberry h.t.

Table 3—Occurrence of tree seedlings (percentage) by shrub canopy cover for Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry habitat types

	Shrub canopy cover		
Occurrence by species	Light (0-33%)	Moderate (33-66%)	Heavy (66-100%)
Douglas-fir/White Spirea Habitat Type			
Percentage of microplots	42	36	22
Lodgepole pine	16	44	40
Ponderosa pine	17	42	41
Douglas-fir	31	32	37
Grand Fir/Mountain Maple Habitat Type			
Number of microplots	34	26	40
Lodgepole pine	20	80	—
Western larch	34	58	8
Ponderosa pine	27	49	24
Douglas-fir	23	14	63
Engelmann spruce	15	20	65
Grand fir	32	38	30
Grand Fir/Blue Huckleberry Habitat Type			
Number of microplots	28	35	37
Lodgepole pine	12	60	28
Ponderosa pine	28	45	27
Douglas-fir	35	22	43
Engelmann spruce	46	17	37
Grand fir	26	25	49

While the large occurrence of shade-tolerant species on moderately or heavily shaded plots would be expected, the high occurrence of shade-intolerant species on such plots appears incongruent. McConkie and Mowat (1936) found that germination of ponderosa pine in central Idaho was higher under heavy shade, though the death rate of the first-year germinants was also higher under heavy shade than under more intermediate shade or no shade. The net effect at the end of the year was an increase in seedling occurrence with increasing shade. This relationship may hold for many years. The presence of a shade-intolerant species under heavy shade may indicate a safe site—that is, a favorable microenvironment for germination and establishment. However, other safe sites such as a safe site with light shade may provide for faster seedling growth.

Several safe site covers were encountered for the various seedlings throughout the three habitat types (table 4). While the cover RE values often varied considerably between habitat types for the same conifer seedling species, in some cases the RE values for cover species were consistently high or low across habitat types. Notably, thimbleberry (*Rubus parviflorus*) was very efficient for lodgepole pine, ponderosa pine, Douglas-fir, Engelmann spruce, and grand fir in the grand fir/blue huckleberry h.t. and for ponderosa pine and Engelmann spruce in the grand fir/mountain maple h.t. Cover of forbs and grasses and sedges was consistently either very inefficient or inefficient for all species in all three habitat types. The use of a "cover species" and the associated RE value does not intend to imply that a particular cover precludes or is required to obtain a particular seedling. In many cases, the relationship between the cover species and the seedling species may be coincidental; the seedling and the cover species may merely have established in the same location at the same time. On the other hand, a very high or very low RE value may indicate a relationship. The particular cover species may be established in a microenvironment that is favorable or unfavorable to a particular conifer species, and therefore can be used as an indicator of a suitable or unsuitable microenvironment. An example of such a species is Sitka alder (*Alnus sinuata*), which is a very efficient cover species for Engelmann spruce in the grand fir/mountain maple h.t. Sitka alder often occurs in wetter portions of the grand fir/mountain maple h.t., indicating areas that are well suited to Engelmann spruce (Steele and Geier-Hayes 1985). Other cover species may by their characteristics affect the safe site. On one hand, an allelopathic species may preclude the formation of a safe site. On the other hand, a species that supports nitrogen-fixing organisms may create a safe site by providing a favorable rooting environment.

Table 4—Regeneration efficiency (RE)[1] classes for shrub canopies and other microsites for Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry habitat types

Type of cover	Constancy	Area occupied	Species					
			Lodgepole pine	Western larch	Ponderosa pine	Douglas-fir	Engelmann spruce	Grand fir
			Percent					
Douglas-fir/White Spirea Habitat Type								
None	—	—	[2]68	—	41	5	—	—
Grasses and sedges	100	20	—	—	[3]1	1	—	—
Forbs	100	18	—	—	—	2	—	—
Spiraea betulifolia	70	17	4	—	3	4	—	—
Pinus ponderosa	34	11	—	—	3	3	—	—
Prunus spp.	39	7	—	—	—	1	—	—
Slash	57	5	—	—	3	4	—	—
Symphoricarpos spp.	31	4	—	—	3	2	—	—
Amelanchier alnifolia	23	4	—	—	3	3	—	—
Berberis repens	40	3	—	—	—	2	—	—
Ribes spp.	10	2	—	—	—	2	—	—
Populus tremuloides	4	1	—	—	—	2	—	—
Ceanothus velutinus	28	1	—	—	4	4	—	—
Salix scouleriana	7	1	—	—	3	3	—	—
Pseudotsuga menziesii	6	1	—	—	3	—	—	—
Purshia tridentata	5	<1	—	—	4	4	—	—
Pinus contorta	3	<1	5	—	—	3	—	—
Artemisia tridentata	2	<1	—	—	5	—	—	—
Rosa spp.	10	<1	—	—	—	3	—	—
Rubus parviflorus	1	<1	—	—	—	—	—	—
Lonicera utahensis	2	<1	—	—	—	—	—	—
Sorbus scopulina	1	<1	—	—	—	—	—	—
Acer glabrum	2	<1	—	—	—	—	—	—
Physocarpus malvaceus	<1	<1	—	—	—	—	—	—
Sambucus racemosa	1	<1	—	—	—	—	—	—
Grand Fir/Mountain Maple Habitat Type								
None	—	—	25	24	27	14	18	19
Forbs	97	17	—	—	1	2	2	2
Rubus parviflorus	27	15	—	3	5	3	5	2
Ceanothus velutinus	35	13	—	2	2	3	—	3
Grasses and sedges	66	9	—	—	—	—	—	1
Salix scouleriana	32	8	—	—	2	3	2	3
Slash	76	6	—	—	—	3	2	2
Pinus ponderosa	24	6	—	—	3	2	—	2
Ribes spp.	46	5	—	5	4	3	—	3
Vaccinium globulare	21	4	—	5	4	4	3	4
Physocarpus malvaceus	24	4	—	—	—	1	4	4
Abies grandis	12	3	5	—	2	1	—	2
Alnus sinuata	6	3	—	—	—	—	5	2
Lonicera utahensis	26	3	5	5	3	3	—	3
Acer glabrum	18	2	—	—	—	4	—	5
Spiraea betulifolia	30	2	—	—	—	2	—	2
Pseudotsuga menziesii	15	2	—	—	—	2	—	3
Prunus spp.	8	2	—	—	—	3	—	2
Symphoricarpos spp.	13	1	—	—	—	3	—	—
Pachistima myrsinites	3	<1	—	—	—	4	—	—
Sorbus scopulina	5	<1	—	—	—	—	5	—
Amelanchier alnifolia	6	<1	—	—	—	—	—	—
Rosa spp.	25	<1	—	—	5	3	—	—
Larix occidentalis	<1	<1	—	—	—	4	—	—
Shepherdia canadensis	2	<1	—	—	—	—	—	5
Picea engelmannii	2	<1	—	—	—	—	—	—
Populus tremuloides	1	<1	—	—	—	—	—	—
Artemisia tridentata	1	<1	—	—	5	—	—	—
Clematis columbiana	2	<1	—	—	—	5	—	—
Sambucus racemosa	3	<1	—	—	—	—	—	—
Berberis repens	3	<1	—	—	—	—	—	—

(con.)

Table 4 (Con.)

Type of cover	Constancy	Area occupied	Species					
			Lodgepole pine	Western larch	Ponderosa pine	Douglas-fir	Engelmann spruce	Grand fir
			Percent					
			Grand Fir/Blue Huckleberry Habitat Type					
None	—	—	10	—	31	13	11	7
Grasses	90	17	—	—	2	—	—	1
Forbs	96	13	—	—	—	2	2	1
Vaccinium globulare	52	13	4	—	4	4	4	4
Pinus ponderosa	34	10	—	—	—	2	2	4
Salix scouleriana	36	9	—	—	—	3	4	4
Lonicera utahensis	42	6	5	—	—	2	4	1
Alnus sinuata	10	5	—	—	—	—	—	2
Ceanothus velutinus	13	5	—	—	—	2	—	3
Ribes spp.	50	5	—	—	4	3	2	3
Abies grandis	10	4	—	—	—	—	—	—
Slash	62	3	—	—	—	—	—	4
Spiraea betulifolia	38	3	5	—	—	4	3	3
Pinus contorta	8	2	—	—	—	—	—	—
Larix occidentalis	4	1	—	—	—	—	—	—
Shepherdia canadensis	3	<1	—	—	—	—	—	—
Pseudotsuga menziesii	10	1	—	—	—	—	—	—
Rubus parviflorus	14	<1	5	—	5	5	5	5
Sambucus racemosa	4	<1	—	—	—	—	—	—
Pachistima myrsinites	8	<1	—	—	—	5	—	—
Picea engelmannii	4	<1	—	—	—	—	5	—
Rosa spp.	16	<1	—	—	—	—	—	—
Symphoricarpos oreophilus	1	<1	—	—	—	—	—	—
Amelanchier alnifolia	3	<1	—	—	5	—	—	—
Physocarpus malvaceus	1	<1	—	—	—	—	—	—
Sorbus scopulina	2	<1	—	—	—	—	—	—
Prunus spp.	2	<1	—	—	—	—	—	—

[1]Regeneration efficiency is the percentage occurrence of the seedling species divided by the percentage occurrence of the safe site component.

[2]During sampling, no estimate of "none" type of cover was made for each plot. Therefore, this value is the percentage of seedlings that had no cover. The remaining percentage is represented in the RE value for the type of cover under which the seedling was found.

[3]Class 1: 0 to 0.25, very efficient; class 2: 0.26 to 0.75, inefficient; class 3: 0.76 to 1.50, efficient; class 4: 1.51 to 3.00, moderately efficient; class 5: 3.01 and greater, very efficient.

Site Treatment

The cover species and seedbeds that remain on the site after timber harvesting are influenced by the type of site preparation used to dispose of slash or prepare for artificial regeneration. For most species in most habitat types, scarification resulted in the largest proportion of seedlings (table 5). Moss mats, which were moderately efficient or very efficient seedbeds for most species, usually occurred on sites that had been scarified and occasionally on sites that had been broadcast burned. Broadcast burning resulted in the largest proportion of Douglas-fir seedlings in both the Douglas-fir/white spirea and grand fir/blue huckleberry h.t.

Table 5—Occurrence of tree seedlings (percentage) by site preparation methods for Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry habitat types

Species	No preparation	Broadcast burn	Scarification	
			Light	Heavy
Douglas-fir/White Spirea Habitat Type				
Percentage of microplots	6	15	50	29
Lodgepole pine	—	41	59	—
Ponderosa pine	19	22	44	15
Douglas-fir	8	58	27	7
Grand Fir/Mountain Maple Habitat Type				
Number of microplots	15	7	55	23
Lodgepole pine	—	—	100	—
Western larch	—	—	87	13
Ponderosa pine	29	14	12	45
Douglas-fir	24	4	35	37
Engelmann spruce	—	—	80	20
Grand fir	17	27	33	23
Grand Fir/Blue Huckleberry Habitat Type				
Number of microplots	4	11	64	21
Lodgepole pine	—	29	42	29
Ponderosa pine	—	—	80	20
Douglas-fir	—	39	36	25
Engelmann spruce	—	—	67	33
Grand fir	—	38	24	38

Silvicultural Methods

Silvicultural activities influence the safe site both by altering the availability of site protection and by influencing the dispersal of seed to the safe site. In the Douglas-fir/white spirea h.t., the largest proportion of lodgepole pine and ponderosa pine seedlings was found under shelterwood cuts (table 6). As would be expected, seedlings occurred predominately in cutting units with a seed source for the particular species present within or close to the cutting unit. In the grand fir/mountain maple h.t., only Engelmann spruce and grand fir were most common in shelterwoods. Western larch and Douglas-fir occurred predominately in seed-tree cutting units. In the grand fir/blue huckleberry h.t., lodgepole pine and Engelmann spruce were most common in shelterwood cuts, while ponderosa pine, Douglas-fir, and grand fir were predominate in clearcuts.

Species

Lodgepole Pine—Lodgepole pine regenerated best under shelterwood cuts in the Douglas-fir/white spirea and grand fir/blue huckleberry h.t. and best under seed-tree cuts in the grand fir/mountain maple h.t. Lodgepole pine is mostly nonserotinous in central Idaho (Steele and others 1981), and the high incidence of lodgepole pine seedlings under the shelterwood was probably because of an adequate seed source rather than the environmental conditions provided by the residual overstory. In south-central Oregon, Dahms (1963) found that 85 percent of the seed dispersed into clearcuts fell within 66 ft (20 m) of the seed source. Boe (1956) reported that in central Montana, 84 percent of the seed fell within 198 ft (60 m) of the seed source. Dahms (1963) recommends that clearcutting units should not be larger than 400 ft (122 m) across. Trappe (1959) suggests using long, narrow clearcuts or seed-tree cuts with seed-trees placed not more than 198 ft (60 m) apart.

For all three habitat types, most seedlings occurred on sites with light scarification. Trappe (1959), Boe (1956), Day and Duffy (1963), and Roe (1952) also found that lodgepole pine occurred most often on scarified sites on mineral soil. In central Idaho, mineral soil or moss mats were efficient, moderately efficient, or very efficient seedbeds. Most seedlings occurred in moderate shade in all three habitat types. Several covers were moderately efficient or very efficient for lodgepole pine including Utah honeysuckle (*Lonicera utahensis*), thimbleberry, blue huckleberry, and white spirea.

Western Larch—Western larch seedlings occurred exclusively in the grand fir/mountain maple h.t. Most seedlings were found under seed-tree cuts with a western larch overstory, particularly on sites with scarification. Boe (1953) found that western larch in northwestern Montana dispersed seed up to 396 ft (121 m). Shearer (1959), also working in northwestern Montana, reported that virtually all seed that disseminated farther than 264 ft (80 m) were released during good seed years and that the smaller the seed crop, the shorter the average dispersal distance. Shearer also indicated that most of the seed was disseminated by thermal slope winds generated by warm, dry weather rather than by prevailing winds. Boyd (1969) found in northern Idaho that clearcuts ranging from 264 to 462 ft wide (80 to 141 m) produced more seedlings than seed-tree cuts or shelterwood cuts. Mineral soils were the most common seedbeds in other areas (Boyd and Deitschman 1969; Roe 1952). However, in central Idaho, moss mats and rotten wood were very efficient seedbeds. Even though Roe (1952) found more western larch seedlings in light shade, most seedlings in central Idaho were found in moderate shade, particularly under blue huckleberry, currant (*Ribes* spp.), and Utah honeysuckle.

Table 6—Occurrence of tree seedlings (percentage) by silvicultural method and overstory composition for Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry habitat types

Silvicultural method	Percent cover	Percentage of sites	Species					
			Lodgepole pine	Western larch	Ponderosa pine	Douglas-fir	Engelmann spruce	Grand fir
Douglas-fir/White Spirea Habitat Type								
Clearcut		58	20	—	22	28	—	—
Seed-tree cut		18	0	—	21	26	—	—
Seedling occurrence (percent) within seed-tree cuts								
Ponderosa pine	7	67	—	—	100	[1]45	—	—
Ponderosa pine	39	22	—	—	—	39	—	—
Douglas-fir	5							
Douglas-fir	15	11	—	—	—	16	—	—
Shelterwood cut		10	80	—	45	26	—	—
Seedling occurrence (percent) within shelterwood cuts								
Lodgepole pine	3	20	100		16	70	—	—
Ponderosa pine	15							
Douglas-fir	6							
Ponderosa pine	16	60	—	—	37	[1]30	—	—
Ponderosa pine	20	20	—	—	47	—	—	—
Douglas-fir	15							
Selection cut		14	0	—	12	20	—	—
Seedling occurrence (percent) within selection cuts								
Lodgepole pine	15	14	—		—	11	—	—
Ponderosa pine	3							
Douglas-fir	18							
Ponderosa pine	24	43	—	—	—	29	—	—
Douglas-fir	8							
Ponderosa pine	11	29	—	—	14	5	—	—
Douglas-fir	15	14	—	—	[1]86	55	—	—
Grand Fir/Mountain Maple Habitat Type								
Clearcut		66	5	9	12	22	30	20
Seed-tree cut		8	73	84	29	28	70	26
Seedling occurrence (percent) within seed-tree cuts								
Western larch	3	17	—	52	—	—	—	—
Western larch	3	17	100	39	—	—	100	70
Engelmann spruce	6							
Ponderosa pine	3	49	—	[1]9	100	[1]100	—	23
Grand fir	15	17	—	—	—	—	—	7
Shelterwood cut		11	0	7	0	32	0	44
Seedling occurrence (percent) within shelterwood cuts								
Western larch	3	13	—	100	—	56	—	18
Douglas-fir	33							
Grand fir	15							
Douglas-fir	18	13	—	—	—	—	—	13
Douglas-fir	13	61	—	—	—	10	—	5
Grand fir	12							
Grand fir	53	13	—	—	—	[1]35	—	64
Selection cut		14	22	0	59	18	0	10
Seedling occurrence (percent) within selection cuts								
No cover	0	10	—	—	—	—	—	—
Lodgepole pine	3	10	—	—	—	—	—	55
Grand fir	3							
Ponderosa pine	3	10	100	—	—	—	—	—
Douglas-fir	15							
Grand fir	15							
Ponderosa pine	3	20	—	—	27	—	—	—
Grand fir	11							
Douglas-fir	18	10	—	—	—	30	—	16
Douglas-fir	15	10	—	—	—	15	—	24
Grand fir	3							
Grand fir	11	30	—	—	[1]73	[1]55	—	5

(con.)

Table 6 (Con.)

Silvicultural method	Percent cover	Percentage of sites	Species: Lodgepole pine	Western larch	Ponderosa pine	Douglas-fir	Engelmann spruce	Grand fir
			Grand Fir/Blue Huckleberry Habitat Type					
Clearcut		82	26	—	100	56	24	53
Seed-tree cut		7	0	—	44	44	0	24
			Seedling occurrence (percent) within seed-tree cuts					
Ponderosa pine	15	50	—	—	—	—	—	100
Douglas-fir	3							
Engelmann spruce	3							
Douglas-fir	3	50	—	—	—	100	—	—
Grand fir	3							
Shelterwood cut		7	74	—	0	0	76	7
			Seedling occurrence (percent) within shelterwood cuts					
Lodgepole pine	1	50	—	—	—	—	—	—
Grand fir	53							
Douglas-fir	15	50	100	—	—	—	100	100
Engelmann spruce	3							
Grand fir	18							
Selection cut		4	0	—	0	0	0	16
			Seedling occurrence (percent) within selection cuts					
Engelmann spruce	18	100	—	—	—	—	—	100
Grand fir	45							

[1]Seed source within 100 feet (30 m) of sample plot.

Ponderosa Pine—Ponderosa pine occurred most often in the warm, dry Douglas-fir/white spirea h.t. Here, ponderosa pine regeneration was highest under shelterwoods, while in both of the cooler, moister grand fir habitat types, regeneration was highest under selection cuts and on clearcuts. Ponderosa pine seed does not disseminate naturally over long distances; in central Oregon, most seed fell within 132 ft (40 m) of the seed source (Barrett 1966). Curtis and Foiles (1961) reported that in central Idaho, most ponderosa pine seed fell within 66 ft (20 m) of the seed source.

As with the lodgepole pine and western larch, scarification treatments produced the largest number of ponderosa pine seedlings. Tackle and Roy (1953), Roy (1983), and Shearer and Schmidt (1970) indicated that scarification treatments resulted in more seedlings than did other treatments. Foiles and Curtis (1965) reported that the seed-to-seedling ratio was 55:1 on scarified areas, while the ratio was 6,150:1 on unscarified areas. In the Douglas-fir/white spirea and grand fir/blue huckleberry h.t., light scarification was best, while in the grand fir/mountain maple h.t., most seedlings occurred from heavy scarification. Moss mats, rotten wood, and bare soil were moderately efficient and very efficient seedbeds in the Douglas-fir/white spirea and the grand fir/blue huckleberry h.t. Most seedlings were found in moderate shade in all three habitat types. Big sagebrush (*Artemisia tridentata*), thimbleberry, rose (*Rosa* spp.), and serviceberry (*Amelanchier alnifolia*) were very efficient covers.

Not all of the incidences of ponderosa pine resulted from natural seedfall. In the Douglas-fir/white spirea h.t., 16 percent of the occurrences of ponderosa pine resulted from seed caches. In both the grand fir/mountain maple and grand fir/blue huckleberry h.t., 17 percent of the occurrences were in seed caches. In central Idaho, McConkie and Mowat (1936) found that 14 percent of the ponderosa pine occurrences were the result of seed caches. Saigo (1969) and West (1968), both working on the east side of the central Oregon Cascades, found that seedling caches occurred 21 and 15 percent, respectively.

Various animals have been implicated as the source of these seed caches. Giuntoli and Mewaldt (1978), in the Bitterroot Range in Montana, found that Clark's nutcracker (*Nucifraga columbiana*) ate and probably cached ponderosa pine seed in the same manner that limber pine (*Pinus flexilis*) and whitebark pine (*P. albicaulis*) are stored (Giuntoli and Mewaldt 1978; Lanner and Vander Wall 1980; Vander Wall and Balda 1977; Vander Wall and Hutchins 1983). Saigo (1969) indicated that most seed caches in her study area probably resulted from the golden-mantled ground squirrel (*Spermophilus lateralis*) or the yellow pine chipmunk (*Eutamias amoenus*). Both of these rodents are present in central Idaho. However, the yellow pine chipmunk was probably most common within the studied habitat types (Steele 1986). Other animals in the study areas, namely the Steller's jay (*Cyanocitta stelleri*) and deer mouse (*Peromyscus maniculatus*), also cache seed. However, these animals cache single seeds rather than groups of seed (Hofmann 1923; Lanner 1980). Seedlings that may have resulted from single seed caches could not be distinguished from seedlings that resulted from natural seedfall.

Douglas-fir—Douglas-fir occurrence was similar to the occurrence of ponderosa pine. It was highest in the Douglas-fir/white spirea h.t. and lowest in the grand fir/blue huckleberry h.t. Douglas-fir seedlings were found in

almost equal amounts under different silvicultural treatments in the Douglas-fir/white spirea h.t., though occurrence in clearcuts was slightly higher than occurrences under other treatments. However, in the grand fir/blue huckleberry h.t., more than half of the Douglas-fir seedlings were found in clearcuts. In grand fir/mountain maple, more seedlings were found under shelterwoods. In northwestern Montana, Douglas-fir seed dispersed up to 264 ft (80 m) (Boe 1953). Boyd (1969) found that most seedlings occurred in clearcuts in northern Idaho though slightly fewer were found in shelterwood cuts, while Day and Duffy (1963), working in Canada, recommend shelterwood cutting.

Scarification treatments favored Douglas-fir seedlings in both grand fir habitat types. However, broadcast burning was most beneficial in the Douglas-fir/white spirea h.t. Moderately efficient seedbeds were moss mats in Douglas-fir/white spirea and grand fir/mountain maple h.t., residual duff in grand fir/mountain maple h.t., and rotten wood in grand fir/blue huckleberry h.t. Roe (1952) found most seedlings on mineral soil, but Day and Duffy (1963) reported that moss mats and decayed wood were better seedbeds than mineral soil. In the Douglas-fir/white spirea h.t., white spirea, ceanothus (*Ceanothus velutinus*), slash, and bitterbrush (*Purshia tridentata*) were moderately efficient cover. Blue huckleberry, mountain maple, and pachistima (*Pachistima myrsinites*) were moderately efficient in grand fir/mountain maple h.t., and thimbleberry and pachistima were very efficient in grand fir/blue huckleberry h.t. Most seedlings were found under heavy canopy cover. On other areas, seedlings were found more commonly under light or moderate cover (Roe 1952) or no cover (Day and Duffy 1963).

Engelmann Spruce and Grand Fir—Both Engelmann spruce and grand fir occurred only in the grand fir habitat types. Engelmann spruce seedlings were predominate under seed-tree cuts in grand fir/mountain maple h.t. and under shelterwoods in grand fir/blue huckleberry h.t. Squillace (1954), working in Montana, suggested that openings of 1,188 ft (362 m) to 1,320 ft (402 m) are maximum size for obtaining good Engelmann spruce regeneration. However, Alexander (1969) in Colorado reported that most seed fell within 198 ft (60 m) of the seed source even though seed was dispersed as far as 396 ft (121 m) during years of moderate seed production. Ronco (1973) found that most seed fell within 99 ft (30 m). Alexander and others (1986) recommended that clearcut openings should be no larger than 450 ft (137 m). Roe (1952) states that clearcutting should only be used on north or east aspects when Engelmann spruce seedlings are desired; shelterwood cuts should be used on south or west aspects. Boyd (1969) found that more seedlings occurred in clearcuts in northern Idaho than in seed-tree cuts or shelterwood cuts.

All seedlings were found on sites with scarification, predominately light scarification. Roe (1952), Boyd and Deitschman (1969), Smith (1954), and Fiedler and others (1985) all reported that most Engelmann spruce seedlings occurred on scarified sites with exposed mineral soil. Day (1964) and Day and Duffy (1963) found that moss and decayed wood were better seedbeds than was mineral soil. In central Idaho, moss mats were very efficient seedbeds in all three habitat types. Most seedlings occurred under heavy shade in grand fir/mountain maple h.t., and under light shade in grand fir/blue huckleberry h.t. Thimbleberry, Sitka alder, and mountain ash (*Sorbus scopulina*) were very efficient covers in grand fir/mountain maple h.t. Thimbleberry, Engelmann spruce, and Scouler willow (*Salix scouleriana*) were very efficient or moderately efficient in grand fir/blue huckleberry h.t.

Most grand fir seedlings were found under shelterwoods in grand fir/mountain maple h.t. and in clearcuts in grand fir/blue huckleberry h.t. Boyd (1969) in northern Idaho found more grand fir seedlings in seed-tree cutting units than in clearcuts or shelterwood cuts. Seedling occurrence was highest on scarified sites in both habitat types. Residual duff was a very efficient seedbed in grand fir/mountain maple h.t., and rotten wood was very efficient in grand fir/blue huckleberry h.t. More seedlings occurred in moderate or heavy shade. Mountain maple and russet-buffaloberry (*Shepherdia canadensis*) were very efficient covers in grand fir/mountain maple h.t., and thimbleberry was very efficient in grand fir/blue huckleberry h.t.

RECOMMENDATIONS

Following are recommendations for the observed species in the Douglas-fir/white spirea, grand fir/mountain maple, and grand fir/blue huckleberry habitat types in central Idaho.

Douglas-Fir/White Spirea Habitat Type

Lodgepole Pine—Because lodgepole pine is mostly nonserotinous in central Idaho (Steele and others 1981) care must be taken to maintain the species' residual overstory. Small clearcuts, seed-tree cuts, and shelterwood cuts can be used. All sites should be lightly scarified. Complete removal of competing vegetation is not necessary because lodgepole pine can establish in moderate shade.

Ponderosa Pine—Ponderosa pine is a heavy-seeded species (Minore 1979), so seed-tree cuts and shelterwoods are effective. Light scarification is desired, but seedlings will establish on heavily scarified sites under bitterbrush and big sagebrush. Seedlings will also establish in moderate shade under ceanothus, which often occurs after broadcast burning.

Douglas-fir—Any silvicultural treatment can be used to establish Douglas-fir seedlings. However, clearcuts should be kept small to ensure adequate seed dispersal from the surrounding stand. Broadcast burning or scarification can both be effective. On scarified sites, scattered slash can be used to protect seedlings.

Grand Fir/Mountain Maple Habitat Type

Lodgepole Pine—The recommendations for lodgepole pine in grand fir/mountain maple h.t. are the same as those for lodgepole pine in the Douglas-fir/white spirea h.t.

Western Larch—Lightly scarified seed-tree cuts are useful to regenerate western larch. Seedlings will establish well under moderate shade of blue huckleberry, currant, and Utah honeysuckle.

Ponderosa Pine—Small clearcuts or ponderosa pine seed-tree cuts with heavy scarification are effective. Seedlings will establish under moderate shade, particularly under thimbleberry and rose.

Douglas-fir—Small clearcuts, seed-tree cuts, or shelterwoods can be used. Douglas-fir seedlings will establish on residual duff, but regeneration is best on sites with light or heavy scarification. Seedlings will establish under most covers, although regeneration may be low on sites with high coverage of ninebark.

Engelmann Spruce—Shelterwoods or brushy seed-tree cuts that have been lightly scarified should regenerate well. Seedlings will establish under heavy shade, particularly on sites with Sitka alder, thimbleberry, and mountain-ash.

Grand Fir—Scarified shelterwoods are best. Broadcast-burned clearcuts that provide moderate shade should also regenerate well.

Grand Fir/Blue Huckleberry Habitat Type

Lodgepole Pine—Small clearcuts, seed-tree cuts, or shelterwood cuts with good lodgepole pine seed sources around or within the cutting unit are effective. Light scarification is best. Seedlings will establish in moderate shade, particularly on sites with Utah honeysuckle, white spirea, and thimbleberry.

Ponderosa Pine—Good seedling establishment should occur on small, lightly scarified clearcuts or seed-tree cuts with well-placed seed-trees. Seedlings should establish well in moderate shade, especially on sites with thimbleberry.

Douglas-fir—Small clearcuts and seed-tree cuts should produce good results. Both scarification and broadcast burning can be used. Seedlings will regenerate under heavy shade, particularly on sites with thimbleberry and pachistima.

Engelmann Spruce—Lightly scarified shelterwoods can be used to regenerate Engelmann spruce. Seedlings will do well under light cover, particularly under the cover of thimbleberry, blue huckleberry, Scouler willow, and Utah honeysuckle.

Grand Fir—Small scarified or broadcast-burned clearcuts that produce heavy shade cover will regenerate well. Cover of thimbleberry, blue huckleberry, and Scouler willow should provide good cover.

Even though stocking of natural seedlings currently is low in central Idaho, natural regeneration can be used as a viable alternative to planting. While the results of this study are not conclusive, data from this and other investigations should help to determine the best methods to regenerate natural seedlings. With further study and careful application of silvicultural treatments and site preparations, stocking of natural regeneration should increase in time.

REFERENCES

Alexander, R. R. 1969. Seedfall and establishment of Engelmann spruce in clearcut openings: a case history. Res. Pap. RM-53. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 8 p.

Alexander, R. R.; Edminster, C. B.; Watkins, R. K. 1986. Estimating potential Engelmann spruce seed production on the Fraser Experimental Forest, Colorado. Res. Pap. RM-269. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 7 p.

Barrett, J. S. 1966. A record of ponderosa pine seed flight. Res. Note PNW-38. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 5 p.

Boe, K. N. 1953. Western larch and Douglas-fir seed dispersal in clearcuttings. Res. Note 129. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Rocky Mountain Forest and Range Experiment Station. 3 p.

Boe, K. N. 1956. Regeneration and slash disposal in lodgepole pine clearcuttings. Northwest Science. 30: 1-11.

Boyd, R. J. 1969. Some case histories of natural regeneration in the western white pine type. Res. Pap. INT-63. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Boyd, R. J.; Deitschman, G. H. 1969. Site preparation aids natural regeneration in western larch-Engelmann spruce strip clearcuttings. Res. Pap. INT-64. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 10 p.

Curtis, J. D.; Foiles, M. W. 1961. Ponderosa pine seed dissemination into group clearcuttings. Journal of Forestry. 59: 766-767.

Dahms, W. G. 1963. Dispersal of lodgepole pine seed into clear-cut patches. Res. Note PNW-3. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 7 p.

Daniel, T. W.; Helms, J. A.; Baker, F. S. 1979. Principles of silviculture. San Francisco: McGraw-Hill. 500 p.

Day, R. J. 1964. The microenvironments occupied by spruce and fir regeneration in the Rocky Mountains. Department of Forestry Publication 1037. Ottawa, Canada: Department of Forestry, Forest Research Branch. 25 p.

Day, R. J.; Duffy, P. J. B. 1963. Regeneration after logging in the Crowsnest Forest. Department of Forestry Publication 1007. Ottawa, Canada: Department of Forestry, Forest Research Branch. 32 p.

Fiedler, C. E.; McCaughey, W. W.; Schmidt, W. C. 1985. Natural regeneration in Intermountain spruce-fir forests—a gradual process. Res. Pap. INT-343. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.

Foiles, M. W.; Curtis, J. D. 1965. Natural regeneration of ponderosa pine on scarified group cuttings in central Idaho. Journal of Forestry. 63: 530-535.

Gashwiler, J. S. 1970. Plant and mammal changes on a clearcut in west-central Oregon. Ecology. 51: 1018-1026.

Giuntoli, M.; Mewaldt, L. R. 1978. Stomach contents of Clark's nutcrackers collected in western Montana. Auk. 95: 595-598.

Harper, J. L. 1977. Population biology of plants. San Francisco: Academic Press. 892 p.

Harvey, A. E. 1982. The importance of residual organic debris in site preparation and amelioration for reforestation. In: Baumgartner, D. M., ed. Site preparation and fuels management on steep terrain: symposium proceedings; 1982 February 15-17; Spokane, WA. Pullman, WA: Washington State University, Cooperative Extension: 75-84.

Harvey, A. E.; Jurgensen, M. F.; Larsen, M. J. 1976. Intensive fiber utilization and prescribed fire effects on microbial ecology of plants. Gen. Tech. Rep. INT-28. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 46 p.

Hofmann, J. V. 1923. Furred forest planters. The Scientific Monthly. 16: 280-283.

Knapp, A. K.; Smith, W. K. 1982. Factors influencing seedling establishment of Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) in southeast Wyoming. Canadian Journal of Botany. 60: 2753-2761.

Lanner, R. M. 1980. Avian seed dispersal as a factor in the ecology and evolution of limber and whitebark pines. In: Dancik, Bruce; Higginbotham, Kenneth, eds. Proceedings, 6th North American forest biology workshop; 1980 August 11-13; Edmonton, AB. Edmonton, AB: University of Alberta: 15-48.

Lanner, R. M.; Vander Wall, S. B. 1980. Dispersal of limber pine seed by Clark's nutcracker. Journal of Forestry. 78: 637-639.

McConkie, A.; Mowat, E. L. 1936. A preliminary study of the factors affecting establishment of ponderosa pine and Douglas-fir seedlings in central Idaho. Unpublished preliminary report on file at: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Boise, ID. 66 p.

Minore, D. 1979. Comparative characteristics of northwestern tree species—a literature review. Gen. Tech. Rep. PNW-87. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 72 p.

Minore, D.; Dubrasich, M. E. 1981. Regeneration after clearcutting in subalpine stands near Windigo Pass, Oregon. Journal of Forestry. 79(9): 619-621.

Mueller-Dombois, D.; Ellenberg, H. 1974. Aims and methods of vegetation ecology. New York: John Wiley and Sons. 547 p.

Roe, A. L. 1952. Larch—Douglas-fir regeneration studies in Montana. Northwest Science. 26(3): 95-102.

Ronco, F. 1973. Food reserves of Engelmann spruce planting stock. Forest Science. 19(3): 213-219.

Roy, D. F. 1983. Natural regeneration. In: Rokon, T. E.; Standiford, R. B., eds. Management of the east side pine type in northeastern California. Arcadia, CA: Northern California Chapter, Society of American Foresters: 87-102.

Saigo, B. W. 1969. The relationship of non-recovered rodent caches to the natural regeneration of ponderosa pine. Corvallis, OR: Oregon State University. 98 p. Thesis.

Shearer, R. C. 1959. Western larch seed dispersal over clearcut blocks in northwestern Montana. Proceedings of the Montana Academy of Sciences. 19: 130-134.

Shearer, R. C.; Schmidt, W. C. 1970. Natural regeneration in ponderosa pine forests of western Montana. Res. Pap. INT-86. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 19 p.

Smith, J. H. 1954. A cooperative study of Engelmann spruce-alpine fir silviculture and management. Northwest Science. 28: 157-165.

Squillace, A. E. 1954. Engelmann spruce seed dispersal into a clear-cut area. Res. Note 11. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 4 p.

Steele, R. 1986. [Personal communication]. Boise, ID: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory.

Steele, R.; Geier-Hayes, K. 1985. The grand fir/mountain maple habitat type in central Idaho: succession and management. Boise, ID: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Forestry Sciences Laboratory. 118 p. Preliminary draft.

Steele, R.; Pfister, R. D.; Ryker, R. A.; Kittams, J. A. 1981. Forest habitat types of central Idaho. Gen. Tech. Rep. INT-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 138 p.

Tackle, D.; Roy, D. F. 1953. Site preparation as related to ground cover density in natural regeneration of ponderosa pine. Tech. Pap. 4. Berkeley, CA: U.S. Department of Agriculture, Forest Service, California Forest and Range Experiment Station. 13 p.

Trappe, J. M. 1959. Lodgepole pine clearcuts in northwestern Oregon. Journal of Forestry. 57: 420-423.

Vander Wall, S. B.; Balda, R. P. 1977. Coadaptions of the Clark's nutcracker and the piñon pine for efficient seed harvest and dispersal. Ecological Monographs. 47: 89-111.

Vander Wall, S. B.; Hutchins, H. E. 1983. Dependence of Clark's nutcracker, *Nucifraga columbiana*, on conifer seeds during the postfledging period. The Canadian Field-Naturalist. 97: 208-214.

West, N. E. 1968. Rodent-influenced establishment of ponderosa pine and bitterbrush seedlings in central Oregon. Ecology. 49: 1009-1011.

Geier-Hayes, Kathleen. 1987. Occurrence of conifer seedlings and their microenvironments on disturbed areas in central Idaho. Res. Pap. INT-383. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 12 p.

Microsite seedbeds and covers were surveyed for six conifer species following various silvicultural-site preparation combinations in three central Idaho habitat types. Seedling occurrence was related to seedbeds, cover, site preparation method, and silvicultural method. An index was developed to indicate potential beneficial or detrimental seedbeds or covers for each species. Recommendations are listed for silvicultural-site preparation practices to obtain desired natural regeneration in the three habitat types.

KEYWORDS: natural regeneration, microsites, central Idaho

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

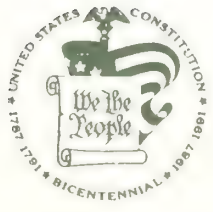
Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.



A 76.17:INT-384

United States
Department of
Agriculture

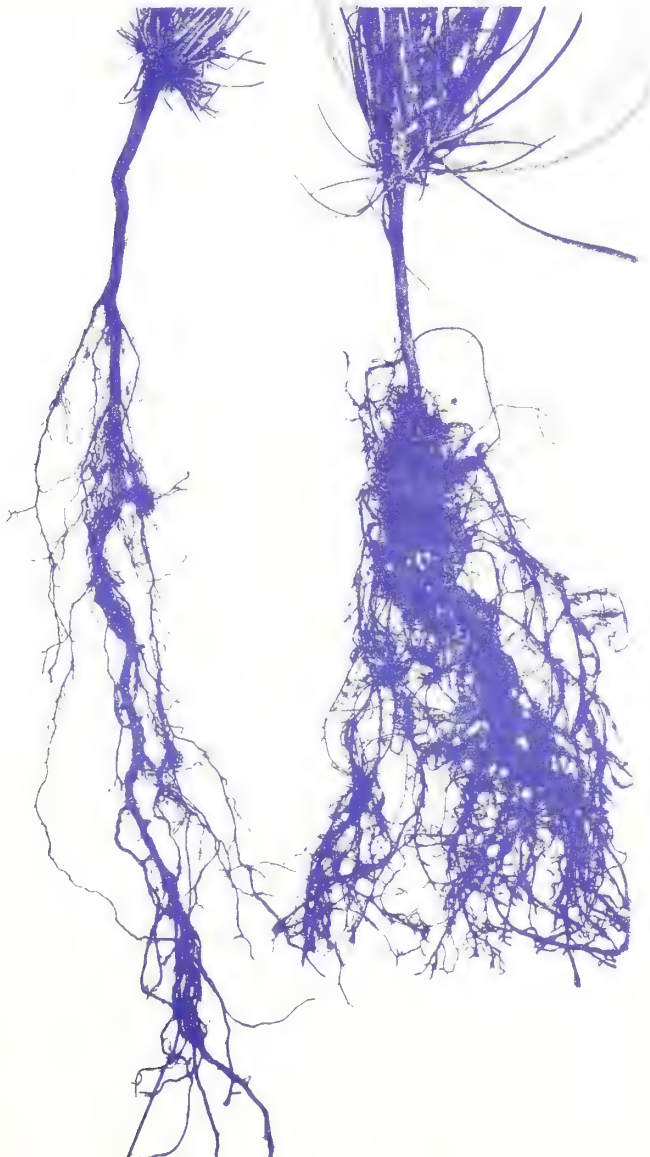
Forest Service

**Intermountain
Research Station**

Research Paper
INT-384

Container-Grown Ponderosa Pine Seedlings Outperform Bareroot Seedlings on Harsh Sites in Southern Utah

John P. Sloan
Lewis H. Jump
Russell A. Ryker



THE AUTHORS

JOHN P. SLOAN is a forester in the Ecology and Regeneration of Rocky Mountain Douglas-fir and Ponderosa Pine research work unit at Boise, ID. He received a B.A. degree in biology from Wartburg College and an M.S. degree in forestry from the University of Minnesota. He joined the Intermountain Station in 1984.

LEWIS H. JUMP is currently a silviculturist on the Greenhorn Ranger District, Sequoia National Forest. During the term of this study he was forest silviculturist on the Dixie National Forest (1979-85). He received a B.S. degree in forest land management from Northern Arizona University in 1971. He joined the Forest Service in 1976 after serving 5 years with the Soil Conservation Service, U.S. Department of Agriculture, in Washington and New Mexico.

RUSSELL A. RYKER was project leader of the Ecology and Regeneration of Rocky Mountain Douglas-fir and Ponderosa Pine research work unit at Boise, ID. He is now retired. He received B.S. and M.S. degrees in forestry from the University of Missouri and conducted research in the silviculture of hardwoods for the North Central Forest Experiment Station prior to joining the Intermountain Research Station in 1963.

RESEARCH SUMMARY

Bareroot and container-grown ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) seedlings were planted on five different habitat types in the Dixie National Forest of southern Utah. After five growing seasons, seedling survival, height, and root form were compared.

Container-grown seedlings survived and grew better than bareroot stock on the harshest sites, but there was little difference between the two on sites more conducive to seedling growth. Although the shapes of container-grown and bareroot root systems were different, the root system coverage in the upper 12 inches of soil was similar.

Container-grown seedling survival ranged from 78 to 98 percent. Bareroot stock survival averaged from 64 to 91 percent. After 5 years since planting, seedling mortality continues on the two harshest sites while leveling off on the better sites. Likewise the mean height-growth rates of container grown seedlings continue to increase over the bareroot trees on the poorest sites but stay even on the best sites.

The report includes a summary of other field tests wherein bareroot and container-grown seedlings of North American conifers were compared.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

October 1987
Intermountain Research Station
324 25th Street
Ogden, UT 84401

Container-Grown Ponderosa Pine Seedlings Outperform Bareroot Seedlings on Harsh Sites in Southern Utah

John P. Sloan
Lewis H. Jump
Russell A. Ryker

INTRODUCTION

Reforestation of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) on the lower elevations of the Dixie National Forest in southern Utah has traditionally been challenging. Replanting has often been necessary, costly, and not always successful. Although this problem is not unique, the low levels of available soil moisture during the spring planting season are probably as critical in the Dixie as anywhere in the Intermountain Region. Until this study was initiated, only bareroot seedlings had been planted.

Elsewhere in North America, container-grown seedlings have been planted in attempts to improve survival and growth in plantations. There have been other reasons for planting container-grown stock as well: to produce nursery stock faster and with less lead time, to produce some species that are difficult to grow in bareroot nurseries, to achieve greater production and planting efficiencies, and to extend planting seasons (Ball and Brace 1982; Barnett 1983; Dickerson and McClurkin 1980; Stein 1974, 1977; Stein and Owston 1976, 1977; Tinus 1976). Operational use of container-grown seedlings, and experimental comparisons between bareroot and container stock have produced mixed results (appendix A). Results may have varied because in many comparisons the container stock was much smaller than the bareroot seedlings (Tinus 1979). Generally the container-grown seedlings have performed very well, especially in recent years.

Several investigators have found that the form of root systems of container-grown trees differs from the form of bareroot seedlings and trees seeded in place. Most natural seedlings of ponderosa pine are characterized by a well-developed taproot, with a few evenly distributed laterals starting just below the root collar (Long 1978; Stein 1978). Stein (1978) calculated the average taproot of natural seedlings to be almost six times longer than the shoot after two growing seasons. Bareroot and container culture affected several root system characteristics, including symmetry, balance, constriction, coiling, taproot development, and root system deformations caused by planting. In most cases there is little difference in root balance and symmetry between container-grown and bareroot stock; however, coiling and constriction are more prevalent in the container-grown trees. The bareroot trees showed a much higher incidence of roots bent in the shape of an L, a J, or knotted, and had fewer well-developed taproots. These differences are still visible from 4 to 7 years after planting (Long 1978). Preisig and others (1979) found more variability in the root form of planted Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) bareroot seedlings than container-grown seedlings; but seedling height was not related to differences in root system morphology for trees 5 to 8 years old.

In container-grown stock, root system deformation is largely affected by the size and design of the container. But with bareroot stock the planter largely determines the root configuration. Budy and Miller (1984) found that after 10 years the container still influenced the root form and number of lateral roots of Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.). Similar comparisons of root form have been documented for lodgepole pine, white spruce (*Picea glauca* [Moench] Voss), Douglas-fir (Van Eerden 1978), lodgepole pine (*Pinus contorta* Dougl.) and white spruce (McMinn 1978), and Douglas-fir and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) (Arnott 1978). Van Eerden (1978) concludes that, although root deformations occur with both container and bareroot seedlings, they do not inevitably lead to plantation failure. Root systems repair themselves and in time acquire a nearly natural habit.

Buchanan (1974) reports mixed results in comparing bareroot ponderosa pine with seedlings grown in Spencer-Lemaire Rootrainers, Styroblocks, Conwed tubes, and peat blocks. Overall, seedling survival with Styroblocks and Rootrainers was close to that of bareroot. Conwed tubes and peat blocks had lower survival.

One and 2 years after planting, survival and growth of container-grown ponderosa pine seedlings was equal to or better than that of seedlings grown in Conwed tubes, Jiffy pots, and Styroblocks planted on the Great Plains (Hite 1974). Although not all field performance showed significant differences, Hite saw an average overall gain in survival of about 20 percent from the use of container-grown seedlings.

This report presents the results of a field comparison between containerized and bareroot ponderosa pine seedlings on the Dixie National Forest after five growing seasons. The administrative study was undertaken by the Dixie National Forest with help from the Intermountain Research Station.

Table 1—Comparison of several characteristics for sites where container stock and bareroot seedlings were tested

Characteristic	Site A	Site B	Site C	Site D	Site E
Ranger District	Cedar City	Cedar City	Powell	Powell	Escalante
Locality	Mammoth Creek Road	Mammoth Cave	Wilson Peak	Dave's Hollow	Allen's Canyon
Parent material	Limestone	Basalt	Limestone	Limestone	Limestone
Soil texture					
0-10 inches	Silt loam	Silt loam	Gravelly loam	Gravelly loam and clay loam	Gravelly silt loam
10-20 inches	Silty clay loam and silt loam	Silty clay loam to silty clay	Very gravelly	Gravelly loam	Gravelly silty clay loam
Percent moisture of soil at 5 bars tension					
4-6 inches	14.06	6.03	19.22	21.52	18.35
10-12 inches	18.22	8.37	23.03	19.99	23.05
Elevation (ft)	8,450	8,100	7,680	7,720	8,260
Slope (pct)	5	4	4	4	10
Aspect	N	N	NE	NE	SE
Habitat type (*Youngblood and* Mauk 1985)	*Abies concolor/ Symphoricarpos oreophilus*	*Pinus ponderosa/ Symphoricarpos oreophilus*	*Pinus ponderosa/ Purshia tridentata* and *Artemisia nova* (transition)	*Pinus ponderosa/ Arctostaphylos patula*	*Abies concolor/ Arctostaphylos patula*
H.t. 50-year ponderosa pine site index classes (ft) (Youngblood and and Mauk 1985)	30 ± 12	45 ± 9	32 ± 3 and 33 ± 8	32 ± 3	34 ± 9

STUDY AREA

In order to ascertain the influence of site conditions on seedling performance, five sites were chosen within the Dixie National Forest, and the test was repeated on each. The study sites were located in the southwestern part of Garfield County, UT, and represent a range of sites on which ponderosa pine is planted on the Dixie.

The ponderosa pine planting season in the Dixie National Forest normally stretches from late March to late May. Soil moisture is usually adequate during that time. Soon afterward, lack of precipitation limits survival and growth. June is the driest month of the growing season, and rainfall during July, August, and September is erratic. Precipitation has averaged 15 inches (381 mm) per year for the last 30 years at Bryce Canyon weather station, elevation 7,911 ft (2,412 m). The average maximum daily temperature peaks around 86° F (30° C) in June and July (Youngblood and Mauk 1985).

Table 1 compares several characteristics for the five study sites. Site B, near Mammoth Cave, is the only one on a basaltic substrate. The other soils were derived from a limestone parent material. Site A, near Mammoth Creek Road, is located at the highest elevation but is only 770 ft (235 m) above the lowest sites, C (Wilson Peak) and D (Dave's Hollow). Site E, with its southeasterly aspect, supports the only study plots which do not face north or northeast. All five sites are different habitat types, but all supported stands dominated by ponderosa pine before they were cut. Although the site index of each habitat type varies, measurements taken by Youngblood and Mauk (1985) indicate that the *Pinus ponderosa/Symphoricarpos oreophilus* habitat type (site B, Mammoth Cave) is the most productive of the five.

METHODS

The comparison test was established in late April of 1981. The same seed source of ponderosa pine was used for both stock types and on all five sites. Container trees were grown at Coeur d'Alene Nursery in Ray Leach Super Cells. The bareroot stock was grown at Lucky Peak Nursery. Container and bareroot seedling heights were similar, but average stem caliper was 20 percent larger for the bareroot trees than the container trees (table 2). The container-grown trees had well-developed root systems limited by the length of the container to 7.5 inches (19 cm). Bareroot trees had 10-inch (25-cm) root

Table 2—Comparison of bareroot and containerized seedling characteristics for ponderosa pine tested in the Dixie National Forest, 1981

Characteristic	Container trees	Bareroot trees
Stock age	1-0	2-0
Root length	19.0 cm	24.7 ± 4.4 cm
Top length	15.0 ± 3.3 cm	15.6 ± 2.8 cm
Stem diameter	3.1 ± 0.6 mm	3.7 ± 0.7 mm
Ovendry weight		
Tops	1.93 g	2.50 g
Roots	0.83 g	0.88 g

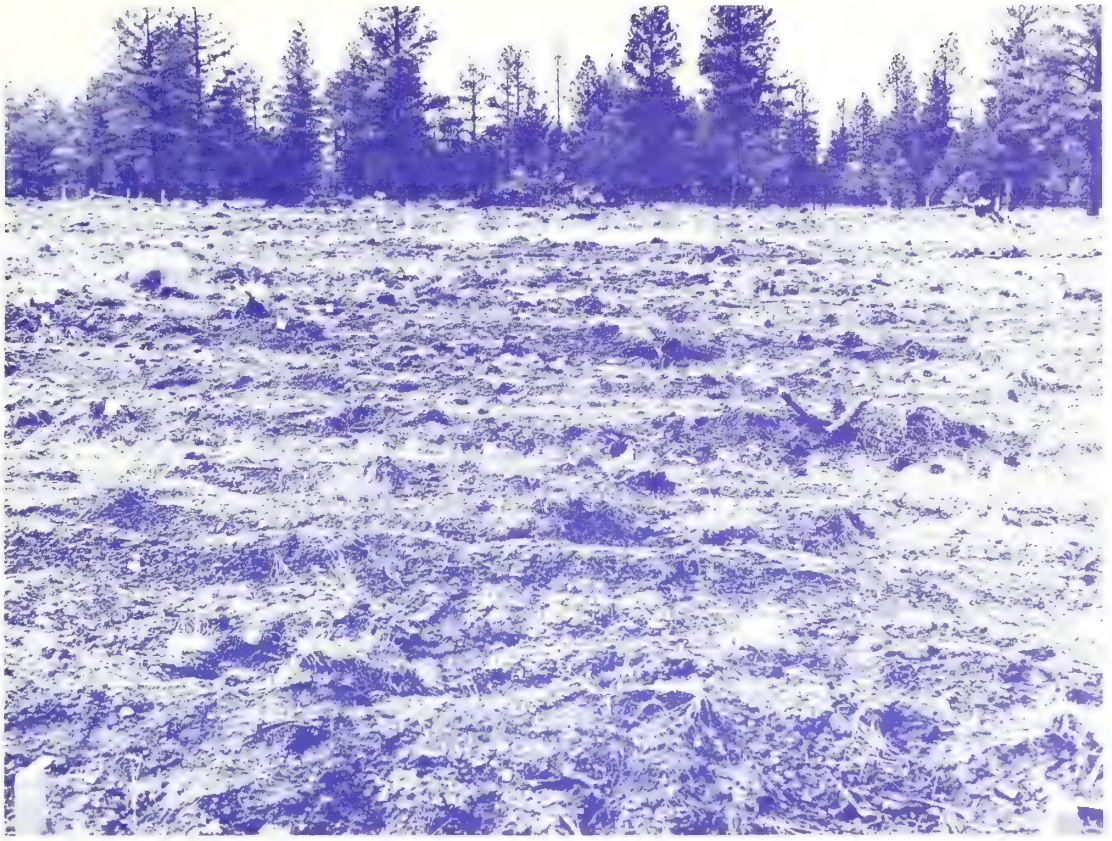


Figure 1—The study site near Wilson Peak after thorough site preparation and shortly before planting.

systems, and many of the roots were stripped during lifting from the nursery beds.

Thorough site preparation was done mechanically on each site, and all five areas were fenced to exclude cattle (fig. 1). Trees of both stock types were auger-planted at the same time. Air and soil temperatures and moisture conditions were generally favorable.

The study was installed with a randomized complete block design comprising 10 blocks per site. Each block contained two plots, one with the bareroot treatment, the other with the container treatment. Trees were spaced 6 by 6 ft (1.8 by 1.8 m). Each plot contained two rows of 10 trees. In other words, 20 container-grown and 20 bareroot seedlings were planted in each block.

Tree survival and heights were measured in the fall of 1981, 1982, 1983, and 1985. In addition, two trees were dug from each plot after the fifth growing season to inspect the roots for growth and form. For each tree that was dug, we calculated a rooting index. This was done by laying the tree on a 1-inch grid and counting the numbers of squares that were intersected by one or more roots. We wanted to account for the third dimension of the root system geometry, so after we measured a seedling the first time, we rotated the stem 90 degrees and measured it once more. We averaged the two measurements to calculate the rooting index for the seedling. This was done for three zones within the upper 12 inches of the root systems: 0-4 inches below the ground surface, 4-8 inches, and 8-12 inches (0-10, 10-20, and 20-30 cm).

RESULTS

After five growing seasons the container-grown ponderosa pine has performed as well as or better than the bareroot stock on all five sites (table 3). Survival ranged from

Table 3—Comparison of mean fifth-year heights and survival of container and bareroot ponderosa pine planted on five sites in the Dixie National Forest. Mean comparisons according to Gabriel (1978)

	Survival	Fifth-year height
	Percent	*cm*
Allen's Canyon		
Bareroot	91*	28.1*
Containerized	98	31.7
Dave's Hollow		
Bareroot	64**	19.6**
Containerized	84	25.7
Mammoth Cave		
Bareroot	91	37.4
Containerized	92	37.8
Mammoth Creek Road		
Bareroot	66*	26.3**
Containerized	78	33.2
Wilson Peak		
Bareroot	84**	31.9
Containerized	96	34.3

*Pairs of means are significantly different (α = 0.05)
**Pairs of means are significantly different (α = 0.01)

64 to 98 percent. The survival differences are statistically significant on four of the five sites. Mammoth Cave is the only site where bareroot stock survived as well as the container-grown seedlings. The biggest difference came at Dave's Hollow, where container-grown trees outsurvived bareroot trees by 20 percent. Dave's Hollow and Mammoth Creek Road sites had the lowest overall survival; Allen's Canyon and Mammoth Cave showed the best survival; Wilson Peak was in between.

Mean height growth on the Mammoth Cave (basalt soil) and Wilson Peak sites was similar for containerized and bareroot trees. But, the height growth of containerized stock was significantly better than that of the bareroot stock on the other three sites. Dave's Hollow showed the biggest difference as well as the poorest overall growth. The best mean growth was measured at Mammoth Cave.

When we excavated a sample of trees 5 years after planting, we found a consistent difference in root form (fig. 2). The root systems of the containerized trees still showed a large mass of roots in the original form of the container plug. From this plug, some lateral roots came out the side but most grew out the bottom. When compared to the containerized stock, the bareroot root systems often did not have as much mass in the upper 12 inches of soil and assumed more of a bell shape.

Table 4 shows the mean rooting index for three root zones. Root zone 1 is 0 to 4 inches (0 to 10 cm) from the ground surface. Root zone 2 is from 4 to 8 inches (10 to 20 cm), and zone 3 is in the 8- to 12-inch (20- to 30-cm) layer. Even though containerized and bareroot root systems are somewhat different in shape, this measurement reveals relatively little difference in total root system in the first 12 inches (30 cm) of soil.

The root index showed trees on the Mammoth Cave site to have more roots in the first 4 inches of soil than on the Dave's Hollow site. The other sites were not different ($\alpha = 0.05$). In the 4- to 8-inch layer, Wilson Peak seedlings had more roots than Mammoth Cave. At 8 to 12 inches from the surface, Wilson Peak was again the best and Mammoth Cave was the worst, but there were also several other differences.

Shoot borer damage to the terminal buds was extensive between the third and fifth growing seasons. The insects did not prefer either container-grown or bareroot seedlings, but there was a difference between sites. The Mammoth Cave and Wilson Peak sites showed the most

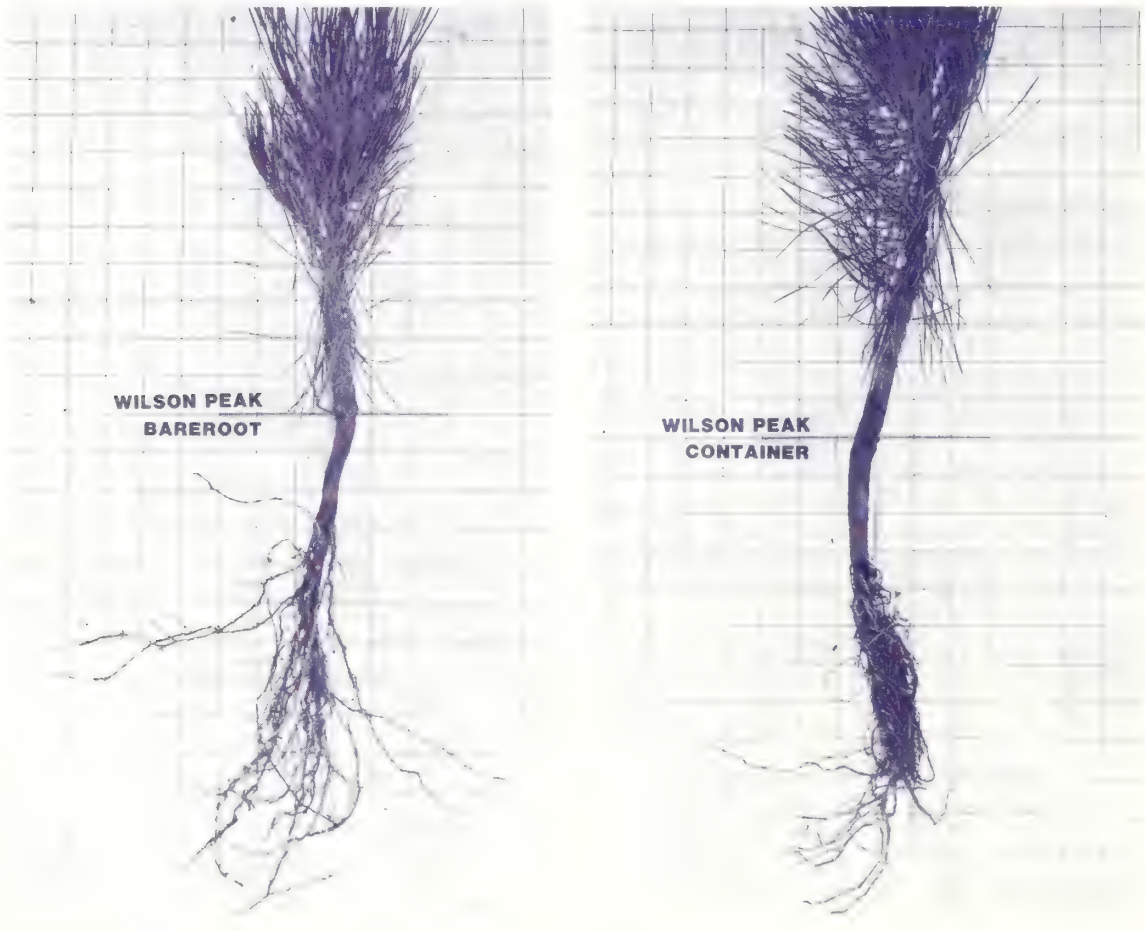


Figure 2—After five growing seasons, the root system forms of container and bareroot ponderosa pine seedlings still show obvious differences. The bareroot tree (left) is shaped like an expanding triangle. The container-grown seedling still has the original plug shape with roots growing out of the bottom. These trees were excavated near Wilson Peak in the Dixie National Forest in September 1985.

Table 4—Mean root index of trees on each site for both treatments and each of three root zones. Larger numbers represent more extensive root system coverage. See text for explanation. Values followed by the same letter are not significantly different (α = 0.01). Mean comparison methods according to Gabriel (1978)

Site and treatment	Zone 1 (0-4 inches)	Zone 2 (4-8 inches)	Zone 3 (8-12 inches)	Zones 1+2+3 (0-12 inches)
Allen's Canyon	9.8 ab	15.8 b	9.5 ab	35.1
Dave's Hollow	8.2 a	12.1 ab	13.5 bc	33.7
Mammoth Cave	10.8 b	10.2 a	4.5 a	25.5
Mammoth Creek Road	8.6 a	12.6 ab	9.7 ab	30.8
Wilson Peak	9.2 ab	16.2 b	17.5 c	42.4
Bareroot	8.8	12.8	10.5	24.4
Containerized	9.7	13.9	11.3	28.5

Figure 3—After five growing seasons on the Allen's Canyon site, few signs of site preparation are evident. The trees are still too small to be conspicuous from a distance. The photo was taken in September 1985.

terminal bud damage from shoot borers. Of all trees surviving after the fifth growing season, 57 and 58 percent showed signs of insect damage, respectively. Mammoth Creek Road and Allen's Canyon sites had about half the leader damage of Mammoth Cave and Wilson Peak (26 percent); Dave's Hollow was intermediate, with 40 percent of live trees infected.

Figure 3 shows how the study site near Allen's Canyon looked in September of 1985, five growing seasons after planting. Most of the vegetation had recovered to prestudy condition.

DISCUSSION

Survival and growth of the ponderosa pine stock differed considerably between sites. Figure 4 compares the yearly survival and height growth of bareroot and containerized stock for all five sites. The order is from best overall performance (top graphs—Mammoth Cave site) to the poorest (bottom graphs—Dave's Hollow site).

After 5 years on the Mammoth Cave site where the trees are the tallest (α = 0.01), there is no difference between the survival and height growth of bareroot compared to containerized stock. But on harsher sites, seedling performance is poorer and container-grown seedlings survive and grow better than bareroot seedlings. Dave's Hollow is the poorest site and the trees are shorter (α = 0.01). Even though the containerized stock at Dave's Hollow did not grow as tall and suffered higher mortality than on other sites, it still performed significantly better than the bareroot stock.

On the other sites seedling survival and growth fell between Mammoth Cave and Dave's Hollow. Again, as survival and height growth improve from site to site, the difference between containerized and bareroot stock diminishes.

Seedling mortality on the best three sites (Mammoth Cave, Allen's Canyon, Wilson Peak) leveled off between the second and third years but has continued on the two harshest sites (Mammoth Creek Road, Dave's Hollow) through the fifth growing season. Survival should not still be declining in the fifth year. Often this indicates an inadequate degree of site preparation. On dry sites in central Idaho, extensive site preparation is needed to ensure ponderosa pine plantation success (Sloan and Ryker 1986).

Heights of container-grown seedlings have continued to increase over the bareroot on the two harshest sites. On the better sites, the margin between bareroot and containerized stock heights has stayed fairly constant. The exception is at Mammoth Cave, where the bareroot trees have caught up since falling behind in the second year (fig. 4).

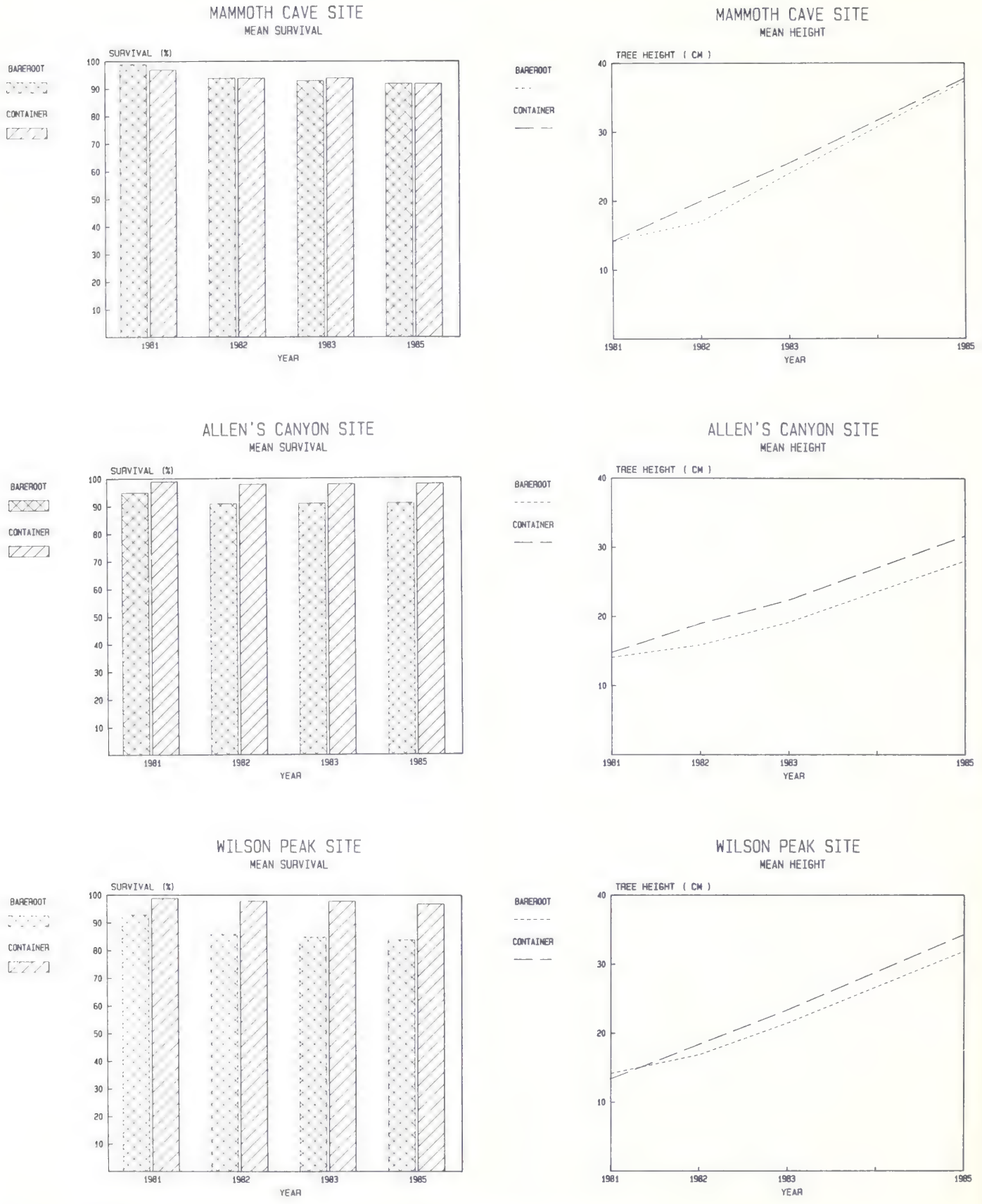


Figure 4—Mean seedling survival and heights of container and bareroot seedlings over five growing seasons on five sites in the Dixie National Forest.

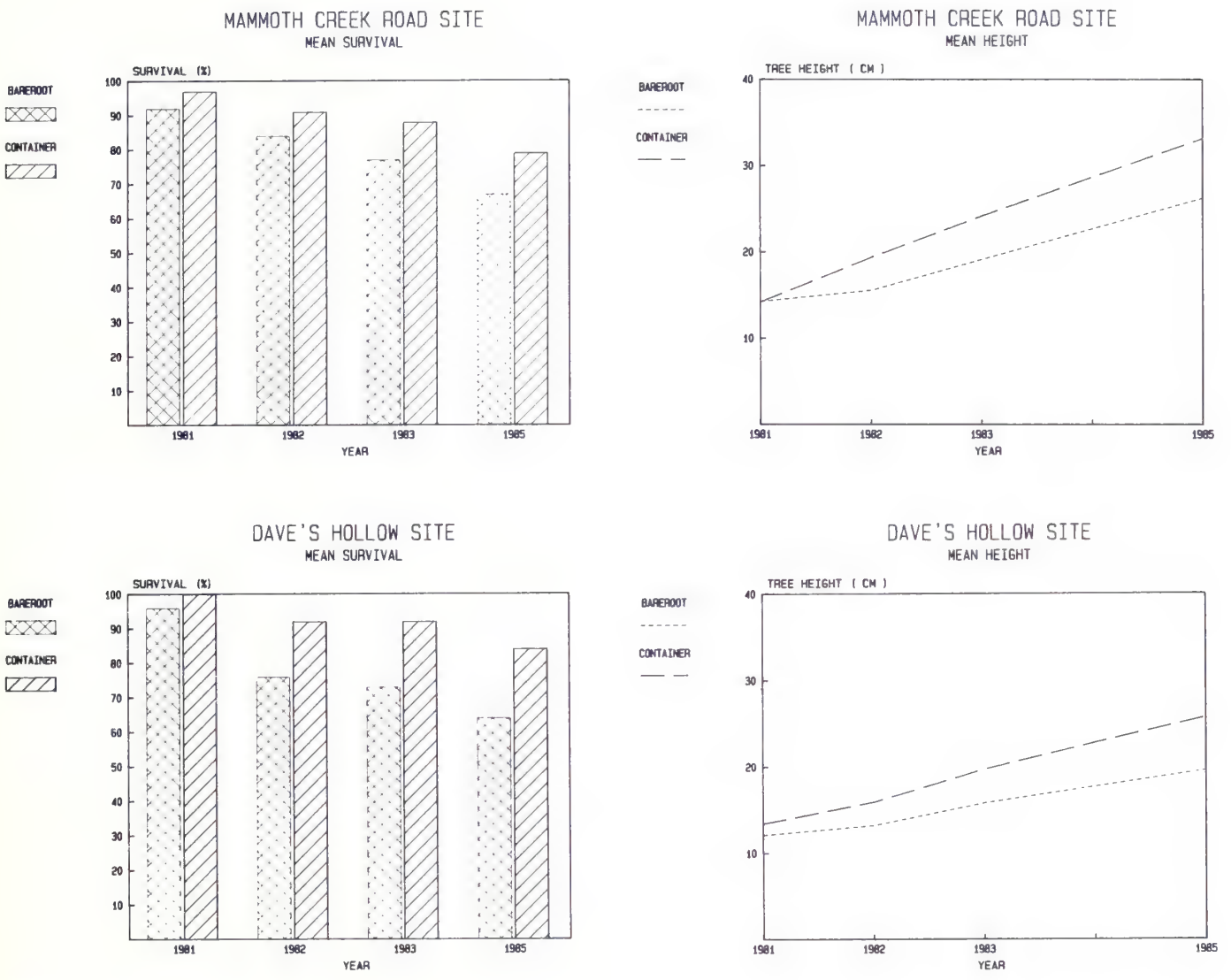


Figure 4 (Con.)

The shoot borer decreased the overall mean heights of the trees but did not affect the results because damage was spread evenly between the bareroot and containerized stock. If anything, the insect damage minimized the difference in height growth between sites because the damage was heaviest on the best sites. There is no evidence that shoot borer damage has affected survival.

Although many of the differences are not statistically significant, the root index in the upper 4 inches of soil followed the fifth year field performance very closely (fig. 4 and table 3). This was not the case in the root zones between 4 and 12 inches, however, perhaps because many roots were stripped when they were excavated from the rocky soil, especially at Mammoth Cave. We found few signs of root deformation in either bareroot or containerized seedlings.

Other studies comparing bareroot and containerized ponderosa pine were mostly in agreement with our results. On a dry site near Rogue River, OR, bareroot ponderosa pine survived and grew better than containerized seedlings (Helgerson 1985). Both performed very well, however, and the differences were small. In tests on the Lincoln National Forest of New Mexico where site and weather conditions are similar to the Dixie, results were mixed (Buchanan 1974). Overall there was no clear winner. Hite (1974) reported superior performance of container-grown seedlings in Rocky Mountain trials.

CONCLUSIONS

Container-grown stock has been used operationally and in field tests throughout North America and has performed very well within the last few years. In the Dixie National Forest in southern Utah, where soil moisture is low following the planting season, container-grown seedlings have shown better overall height growth and survival than similar bareroot stock after five growing seasons. Results on five sites vary from little difference in performance on the best sites to significant differences on the harshest sites. As we move from the best to the poorer quality (fig. 4), seedling survival and fifth year mean heights decrease. Also, on the harshest sites the containerized stock performance becomes superior to that of bareroot stock. Nevertheless, even on the best sites in this

study, seedling growth was slower than what we had hoped for with both treatments.

Although the shape of root systems differed, the amount of roots in the upper 12 inches of soil was similar for both kinds of stock. An infestation of shoot borers reduced the mean heights slightly but was not related to treatment and did not affect our conclusions.

After five growing seasons, survival averaged 90 percent for all containerized grown seedlings and 79 percent for bareroot stock. On the good sites not much is gained by planting containerized trees, but on the poor sites containerized trees will definitely outperform bareroot stock.

REFERENCES

Alm, A. A. 1983. Black and white spruce plantings in Minnesota: container vs bareroot stock and fall vs spring planting. Forestry Chronicle. 59(4): 189-190.

Anderson, Robert L.; Knighten, John L.; Powers, Harry R., Jr. 1984. Field survival of loblolly and slash pine seedlings grown in trays and Ray Leach containers. Tree Planters' Notes. 35(2): 3-4.

Arnott, J. T. 1974. Performance in British Columbia. In: Tinus, R. W.; Stein, W. I.; Balmer, W. E., eds. Proceedings, North American containerized forest seedling symposium; 1974 August 26-29; Denver, CO. Publ. 68. Lincoln, NE: Great Plains Agricultural Council: 283-290.

Arnott, J. T. 1978. Root development of container grown and bareroot stock: coastal British Columbia. In: Proceedings, root form of planted trees symposium; 1978 May 16-19; Victoria, BC. Victoria, BC: Ministry of Forests and Canadian Forestry Service: 257-267.

Arnott, J. T. 1981. Survival and growth of bullet, styroplug and bareroot seedlings on mid-elevation sites in coastal British Columbia. Forestry Chronicle. 57(2): 65-70.

Ball, W. J.; Brace, L. G. 1982. Production, use, and field performance of container seedlings in the prairie provinces. In: Scarratt, J. B.; Glerum, C.; Plexman, C. A., eds. Proceedings, containerized tree seedling symposium; 1981 September 14-16; Toronto, ON. COJFRC Symposium Proceedings O-P-10. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 313-320.

Barnett, James P. 1983. Containerized seedlings for revegetating difficult sites. Journal of Soil and Water Conservation. 38(6): 462-464.

Boyer, William D. 1985. First-year survival of planted longleaf pine bare-root and container stock as affected by site preparation and release. In: Proceedings of the third biennial southern silvicultural research conference; 1984 November 7-8; Atlanta, GA. Gen. Tech. Rep. SO-54. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station: 74-78.

Buchanan, Bruce A. 1974. Containerized seedlings on the Lincoln National Forest. In: Tinus, R. W.; Stein, W. I.; Balmer, W. E., eds. Proceedings, North American containerized forest seedling symposium; 1974 August 26-29; Denver, CO. Publ. 68. Lincoln, NE: Great Plains Agricultural Council: 350-365.

Budy, J. D.; Miller, E. L. 1984. Survival, growth, and root form of containerized Jeffrey pines ten years after planting. In: Murphy, Patrick M., ed. The challenge of producing native plants for the Intermountain area: Intermountain Nurseryman's Association conference; 1983 August 8-11; Las Vegas, NV. Gen. Tech. Rep. INT-168. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station: 82-88.

Dickerson, B. P.; McClurkin, D. C. 1980. A field trial of year-round planting of bullet seedlings. Tree Planters' Notes. 31(2): 21-22.

Gabriel, K. Ruben. 1978. A simple method of multiple comparisons of means. Journal of the American Statistical Association. 73(364): 724-729.

Gardner, A. C. 1982. Field performance of containerized seedlings in interior British Columbia. In: Scarratt, J. B.; Glerum, C.; Plexman, C. A., eds. Proceedings, containerized tree seedling symposium; 1981 September 14-16; Toronto, ON. COJFRC Symposium Proceedings O-P-10. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 299-305.

Gutzwiler, Jerry R.; Winjum, Jack K. 1974. Performance of containerized coniferous seedlings in recent forest regeneration trials in Oregon and Washington. In: Tinus, R. W.; Stein, W. I.; Balmer, W. E., eds. Proceedings, North American containerized forest seedling symposium; 1974 August 26-29; Denver, CO. Publ. 68. Lincoln, NE: Great Plains Agricultural Council: 306-309.

Hahn, Phillip F.; Smith, Allen J. 1983. Douglas-fir planting stock performance comparison after the third growing season. Tree Planters' Notes. 34(1): 33-39.

Helgerson, Ole T. 1985. Survival and growth of planted Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) on a hot, dry site in southwest Oregon. Tree Planters' Notes. 36(4): 3-6.

Hite, Wayne A. 1974. Container field performance in the Rockies and plains. In: Proceedings, North American containerized forest tree seedling symposium; 1974 August 26-29; Denver, CO. Publ. 68. Lincoln, NE: Great Plains Agricultural Council: 306-309.

Hobbs, Stephen D.; Wearstler, Kenneth A., Jr. 1983. Performance of three stocktypes on a skeletal soil. Tree Planters' Notes. 34(3) : 11-14.

Long, James N. 1978. Root system form and its relationship to growth in young planted conifers. In: Proceedings, root form of planted trees symposium; 1978 May 16-19; Victoria, BC. Victoria, BC: Ministry of Forests and Canadian Forestry Service: 222-234.

Marion, Susan P.; Alm, Alvin A. 1986. Performance of fall- and spring-planted bareroot and container-grown red pine (*Pinus resinosa* Ait.). Tree Planters' Notes. 37(2): 24-26.

Mattice, C. R. 1982. Comparative field performance of paperpot and bare-root planting stock in northeastern Ontario. In: Scarratt, J. B.; Glerum, C.; Plexman, C. A., eds. Proceedings, containerized tree seedling symposium; 1981 September 14-16; Toronto, ON. COJFRC Symposium Proceedings O-P-10. Sault Ste. Marie, ON: Canadian Forestry Service, Great Lakes Forest Research Centre: 321-330.

McMinn, R. G. 1978. Root development of white spruce and lodgepole pine seedlings following outplanting. In: Proceedings, root form of planted trees symposium; 1978 May 16-19; Victoria, BC. Victoria, BC: Ministry of Forests and Canadian Forestry Service: 186-190.

Owston, Peyton W. 1972. Field performance of containerized seedlings in the western United States. In: Committee proceedings. Portland, OR: Western Forestry Conservation Association: 109-111.

Owston, Peyton W.; Stein, William I. 1978. Survival, growth and root form of containerized and bare-root Douglas-fir and noble firs seven years after planting. In: Proceedings, root form of planted trees symposium; 1978 May 16-19; Victoria, BC. Victoria, BC: Ministry of Forests and Canadian Forestry Service: 216-220.

Preisig, C. L.; Carlson, W. C.; Promnitz, L. C. 1979. Comparative root system morphologies of seeded-in-place, bareroot, and containerized Douglas-fir seedlings after outplanting. Canadian Journal of Forest Research. 9(3): 399-405.

Ruehle, John L.; Marx, Donald H.; Barnett, James P.; Pawuk, William H. 1981. Survival and growth of container grown and bare-root shortleaf pine with *Pisolithus* and *Thelephora* ectomycorrhizae. Southern Journal of Applied Forestry. 5: 20-24.

Sloan, John P.; Ryker, Russell A. 1986. Large scalps improve survival and growth of planted conifers in central Idaho. Res. Pap. INT-366. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 9 p.

Stein, William I. 1974. Improving containerized reforestation systems. In: Tinus, R. W.; Stein, W. I.; Balmer, W. E., eds. Proceedings, North American containerized forest seedling symposium; 1974 August 26-29; Denver, CO. Publ. 68. Lincoln, NE: Great Plains Agricultural Council: 434-447.

Stein, William I. 1977. Prospects for container grown nursery stock. In: Conference proceedings, tree planting in the northwest; 1976 February 17-19; Pullman, WA. Pullman, WA: Washington State University, Cooperative Extension Service: 89-103.

Stein, William I. 1978. Naturally developed seedling roots of five western conifers. In: Proceedings, root form of planted trees symposium; 1978 May 16-19; Victoria, BC. Victoria, BC: Ministry of Forests and Canadian Forestry Service: 28-35.

Stein, William I.; Owston, Peyton W. 1976. Why use container grown seedlings? In: Western Forestry and Conservation Association, Permanent Association Committee Proceedings. Portland, OR: Western Forestry and Conservation Association: 119-122.

Stein, William I.; Owston, Peyton W. 1977. Containerized seedlings in western reforestation. Journal of Forestry. 75: 575-578.

Tinus, R. W. 1976. Greenhouse container nurseries for better trees. In: Shelterbelts on the Great Plains: Proceedings of the symposium; 1976 April 20-22; Denver, CO. Publ. 78. Lincoln, NE: Great Plains Agricultural Council: 137-140.

Tinus, R. W. 1979. Use of container-grown hardwoods for reforestation. In: Regenerating oaks in upland hardwood forests: Proceedings of the 1979 John S. Wright Forestry Conference; West Lafayette, IN. West Lafayette, IN: Purdue University, Department of Forestry and Natural Resources: 120-125.

Van Eerden, E. 1978. Roots of planted trees in central British Columbia. In: Proceedings, root form of planted trees symposium; 1978 May 16-19; Victoria, BC. Victoria, BC: Ministry of Forests and Canadian Forestry Service: 201-208.

Walker, N. R. 1980. Containerized conifer seedling field performance in Alberta and the Northwest Territories. Inf. Rep. NOR-X-218. Edmonton, AB: Environment Canada, Northwest Forest Research Centre. 32 p.

Youngblood, Andrew P.; Mauk, R. L. 1985. Coniferous forest habitat types of central and southern Utah. Gen. Tech. Rep. INT-187. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 89 p.

APPENDIX: STUDIES THAT HAVE COMPARED FIELD PERFORMANCE OF BAREROOT AND CONTAINERIZED SEEDLINGS IN THE UNITED STATES AND CANADA

Study	Species	Type of container	Time since field planting	Results	Survival	
					Bareroot	Container
			Years		- - - - - *Percent* - - - - -	
Alm (1983)	Black spruce (*Picea mariana* [Mill.] B.S.P.)	Styroblocks	4	Containerized stock survived and grew better than 3-0 bareroot stock.	82,83	94,98
		Paperpots	4	Containerized stock survived and grew better than 3-0 bareroot stock.	82,83	94,99
	White spruce (*Picea glauca* [Moench] Voss)	Styroblocks	4	Containerized stock survived and grew better than 3-0 bareroot stock.	72,86	97,100
		Paperpots	4	Containerized stock survived and grew better than 3-0 bareroot stock.	72,86	94
Anderson and others (1984)	Loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.)	Ray Leach seedling containers	1½	Containerized plugs performed better than bareroot stock grown in trays and planted in the summertime.	64 64	85 86
Arnott (1974)	Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco)	Bullets	3-5	Little difference between bareroot and containerized stock growth rates.	82	58
		Bullet plugs	3-5	Little difference between bareroot and containerized stock growth rates.	82	68
		Styroblocks	1-2	Containerized outperformed bareroot in fall and summer plantings but bareroot performed as well or better than container in other spring and fall plantings.	4-100	28-95
	Western hemlock (*Tsuga heterophylla* [Raf.] Sarg.)	Bullets	3	Containerized stock showed superior survival while growth rates were comparable.	35	49
		Bullet plugs		Containerized stock showed superior survival while growth rates were comparable.	35	59
	Lodgepole pine (*Pinus contorta* Dougl.)	Bullets	5	Little difference in performance of summertime planting.	81-83	81-88
		Bullet plugs	5	Containerized stock performed best.	83	95
		Styroblocks	2	Containerized stock performed best.	44,71	75,77
	White spruce	Bullets	5	Little difference in performance.	62	65
		Bullet plugs	5	Containerized stock performed best.	62	87
		Styroblocks	2	Containerized stock showed superior survival and height growth.	53	92
	Engelmann spruce (*Picea engelmannii* Parry)	Styroblocks	2	Containerized stock showed superior survival.	86,92	69,64

(con.)

APPENDIX (Con.)

Study	Species	Type of container	Time since field planting	Results	Survival	
					Bareroot	Container
			Years		*Percent*	
Arnott (1978)	Douglas-fir	Bullets	5	Bareroot stock survived and grew best on the site with heavy vegetative competition.	71-88	61-69
		Bullet plugs and tubes		Bullet plug performed best on drier sites.	88,71 88,71	78,83 73,66
	Western hemlock	Bullets	5	Containerized stock showed superior survival.	24-36	47-58
		Bullet plugs and tubes			24-36 24,36	61,69 43,45
Arnott (1981)	Douglas-fir	Walter's Bullets	5	Differences were not significant	81	77
		Styroblocks	5	Differences were not significant.	81	84
	Western hemlock	Walter's Bullets	5	Variable results.	63	69
		Styroblocks	5	Containerized stock was superior in survival and height growth.	63	87
Boyer (1985)	Longleaf pine (*Pinus palustris* Mill.)	RL Single cells	1	Containerized stock performance was superior to bareroot and differences were greater on dry sites.	59	80
Buchanan (1974)	Ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.)	Conwed tubes and peat blocks	1	Bareroot stock performed better than containerized stock.	30-40	3-10
		Book planters and styroblocks	1	Results were variable but overall containers performed as well as bareroot.	10-65	20-44
Dickerson and McClurkin (1980)	Loblolly pine	Bullets	3	In plantings made after March, containerized seedlings had greater survival. For trees planted in February and March (shorter storage period) bareroot was best.	0-85	36-69
Gardner (1981)	Douglas-fir	Styroblocks	10	Higher survival rate of containerized stock was not significantly better than bareroot. Bareroot height growth was best but again, not significantly better.	66	75
		Bullets	10	Bareroot survival and growth was significantly higher than containers.	66	53
		Bullet plugs	10	Bareroot stock showed higher survival and height growth. Survival differences were significant.	66	52
	White spruce	Styroplugs	10	There were no differences in survival but bareroot height growth was significantly greater.	87	88

(con.)

APPENDIX (Con.)

Study	Species	Type of container	Time since field planting	Results	Survival	
					Bareroot	Container
			Years		- - - - - *Percent* - - - - -	
		Bullets	10	There was little difference in survival but the bareroot were significantly taller.	87	81
		Bullet plugs	10	There was little difference in survival but the bareroot was significantly taller.	87	81
	Lodgepole pine	Styroblocks	10	There was no significant difference in survival and height growth between containerized and bareroot stock.	82	90
		Bullets	10	There was little difference in survival but bareroot seedlings were significantly taller.	82	81
		Bullet plugs	10	There was little difference in survival but bareroot seedlings were significantly taller.		
Gutzwiler and Winjum (1974)	Douglas-fir	Styroblocks, Bullets, Bullet plugs, and Tree trainers	1-2	Results were mixed. Neither bareroot or containerized seedlings were consistently better than the other in growth. Overall, bareroot seemed to have greater survival.	37-90	05-87
	Western hemlock	Styroblocks	1	Little difference in survival.	84-97	85-99
Hahn and Smith (1983)	Douglas-fir	Styroblocks	3	Containerized stock seemed to perform better than bareroot on north slopes. Containers were clearly superior on south slopes.	84,74	91,96
Helgerson (1985)	Douglas-fir	Ray Leach tubes	2	Bareroot survived and grew better on a very dry site.	99	88
	Ponderosa pine	Ray Leach tubes	2	Bareroot survived and grew better on a very dry site.	98	91
Hite (1974)	Ponderosa pine	Conwed mesh and Jiffy pots	5	Bareroot stock did not survive August planting.	0 0	28-60 50
		Conwed mesh	4	Bareroot stock showed very poor survival in November planting.	8	38-74
		Conwed mesh and Styroblocks		Containerized stock was superior to bareroot in June plantings.	56 56	76,91 73
		Book planters	2	Containerized stock was superior to bareroot.	49	78
	Lodgepole pine	Hillson's	1	Containerized stock outperformed bareroot.	60	89
		Styroblocks	1	Containerized stock outperformed bareroot.	60	98
		Univ. of Idaho	1	Containerized stock outperformed bareroot.		

(con.)

APPENDIX (Con.)

Study	Species	Type of container	Time since field planting	Results	Survival	
					Bareroot	Container
			Years		*Percent*	
Hobbs and Wearstler (1983)	Douglas-fir	Leach cells	2	Containerized stock survived better than bareroot, but growth was about even.	56	91
Marion and Alm (1986)	Red pine (*Pinus resinosa* Ait.)	Styroblock	3-4	Bareroot 2-2 stock was best. Other bareroot stock performed similar to containerized trees except in fall plantings (3-0) bareroot did not survive as well as containers and in spring plantings bareroot (2-0) grew better than containerized stock.	51-97	78-83
Mattice (1981)	Black spruce	Paperpots	5	Results are mixed.	62-85	48-99
	White spruce	Paperpots	2	Mostly little difference in survival and height growth.	89-96	91-96
			5	Little difference except bareroot had higher survival in summer planting.	69,70	45,65
	Jack pine (*Pinus banksiana* Lamb.)	Paperpots	3	Little difference in spring planting but containers showed superior survival and growth in summer planting.	89,11	91,98
Owston (1972)	Douglas-fir	Styroblocks	1	Little difference in survival.	67	73
		Styroblocks	1	Trees on north slopes outperformed those on south slopes, but there was little difference between bareroot and containers.	55,84	49,86
Owston and Stein (1978)	Douglas-fir	1½-yr-old seedlings were transplanted into:	[1]7	Containers showed superior survival and height growth over bareroot seedlings.		
		Quart milk cartons			54	65
		Cardboard tubes			54	71
		Peatpots			54	82
		Plastic mesh tubes			54	71
	Noble fir (*Abies procera* Rehd.)	1½-yr-old seedlings were transplanted into:	[1]7	Containers showed superior survival and height growth over bareroot seedlings.		
		Quart milk cartons			60	66
		Cardboard tubes			60	80
		Peatpots			60	88
		Plastic mesh tubes			60	76
Ruehle and others (1981)	Slash pine	Styroblock	2	Containerized seedling survival and height growth was superior on the moister site while bareroot seedlings survived and grew best on the drier site.	65,57	85,50

(con.)

APPENDIX (Con.)

Study	Species	Type of container	Time since field planting	Results	Survival	
					Bareroot	Container
			Years		*Percent*	
Walker (1980)	Lodgepole pine	Styroblock	5	Containerized seedling survival rates were consistently higher than bareroot. Growth rates were variable.	20-92	70-98
		ARC Sausage	5	Containerized seedling survival rates were consistently higher than bareroot. Growth rates were variable.	20-92	59-98
	White spruce	Styroblock	5	Containerized seedling survival rates were consistently higher than bareroot. Bareroot seedling heights were as great or greater than container.	22-77	58-92
		ARC Sausage	5	Containerized seedling survival rates were consistently higher than bareroot. Bareroot seedling heights were as great or greater than container.	22-77	88-92
	Engelmann spruce	Styroblock	5	Containerized seedling survival rates were consistently higher than bareroot. Bareroot seedling heights were as great or greater than container.	10-40	65-72
		ARC Sausage	5	Survival rates were variable and poor. Bareroot seedling heights were as great or greater than container.	10-40	23-32

[1]See Owston (1972) for third-year results.

Sloan, John P.; Jump, Lewis H.; Ryker, Russell A. 1987. Container-grown ponderosa pine seedlings outperform bareroot seedlings on harsh sites in southern Utah. Res. Pap. INT-384. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 14 p.

Survival and height growth of container-grown and bareroot ponderosa pine seedlings planted on five different habitat types in southern Utah were compared after five growing seasons. Survival of container-grown stock ranged from 78 to 98 percent; bareroot stock, 64 to 91 percent. On good sites there was no difference in growth rates and survival, but on harsh sites container-grown stock proved superior to bareroot stock in both respects.

KEYWORDS: reforestation, *Pinus ponderosa*, tree planting, tree nursery, seedlings, survival, height growth, root system

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-385

Armillaria in the Northern Rockies: Delineation of Isolates Into Clones

**Geral I. McDonald
Neil E. Martin**

CLEMSON
MAY 18 1988
PUBLIC DOCUMENTS

THE AUTHORS

GERAL I. MCDONALD is principal plant pathologist at the Intermountain Research Station's Root Diseases and Soil Biology of Northern Rocky Mountain Forests research work unit in Moscow, ID. He received his B.S. degree in forest management in 1963 and Ph.D degree in plant pathology in 1969 from Washington State University. Since joining the Station in 1966, he has investigated the epidemiology and genetic interaction of the blister rust organism and its hosts. He is now investigating the ecological genetics of conifer interaction with *Armillaria*-caused root rots.

NEIL E. MARTIN is research plant pathologist with the Intermountain Research Station's Root Diseases and Soil Biology of Northern Rocky Mountain Forests research work unit in Moscow, ID. He received his B.S. degree in botany (1961) from Iowa State University, M.S. degree in plant pathology (1964) from South Dakota State University, and Ph.D. degree in plant pathology (1972) from Washington State University. Since joining the Station in 1966, he has researched blister rust, dwarf mistletoe, and root rots.

RESEARCH SUMMARY

A method for segregating a large population of *Armillaria* spp. isolates into clones is described. The method includes statistical analysis as a part of clonal definition. Four kinds of errors were investigated: readers could either (1) agree to or (2) disagree with theory, or disagree when (3) compatibility was expected or (4) when incompatibility was expected. All four errors occurred about 4 percent of the time. The error rate was high enough to require statistical tests of delineation efficiency.

A population of 394 isolates was reduced to 177 clones. Traits common to the clones allowed further condensation into four groups. Ecological behavior (host affinity - rhizomorph production) of these groups suggests that the Northern Rockies may support four *Armillaria* spp. In addition, certain cases of isolates showing compatibility over extended geographic distances suggest the population may contain haploid isolates. The large number of multiple-membered clones is a valuable research resource that will advance the technology of species identification within the genus *Armillaria*.

January 1988

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Armillaria in the Northern Rockies: Delineation of Isolates Into Clones

Geral I. McDonald
Neil E. Martin

INTRODUCTION

Soil-inhabiting fungi belonging to the genus *Armillaria* cause root disease and decay on most woody plant species throughout the world (Wargo and Shaw 1985). Recent findings have contributed to an understanding of the taxonomy (Korhonen 1978; Morrison and others 1985; Ullrich and Anderson 1978), physiologic interaction (Wargo 1984), and ecological relationships (McDonald and others 1987) of the genus.

Knowledge about distribution and behavior of *Armillaria* spp. in several regions has appeared in recent years. Two reports published in 1978 outlined the concept of intersterility groups and mapping of the geographic extent of clones. One dealt with the genus in the northeastern portion of North America (Ullrich and Anderson 1978) and the other with *Armillaria* in Finland (Korhonen 1978). The above authors outlined necessary technology to map the extent of both vegetative and sexually active clones. Isolates will fail to join together because they belong to different intersterility groups or they are different genotypes within the same group.

These reports, together with more recent information, supply technology necessary to tentatively identify the taxonomic affiliation of vegetatively delineated clones, provided that fresh basidiospores of all species represented in the vegetative population are available. Six intersterile groups have been identified in Europe. Their taxonomic affinities were demonstrated using these techniques. The groups are as follows: Korhonen's (1978) group D = *Armillaria mellea* (Vahl:Fr.) Kummer, group A = *A. borealis* Marxmuller et Korhonen, group E = *A. bulbosa* (Barla) Watling, group B = *A. cepistipes* Velenosvsky, and group C = *A. ostoyae* (Romagnesi) Herink (Roll-Hansen 1985).

Ten intersterility groups were found in North America (Anderson and Ullrich 1979). Two of the 10 were later consolidated with two others, which resulted in eight groups (Anderson 1986). In the meantime, an additional intersterile group was proposed (Morrison and others 1985). Genetic and taxonomic connections were recently reported among *A. mellea* (North American group VII) growing in the State of Virginia and Korhonen's group D. In addition these connections were shown between *A. bulbosa* (North American group VII) growing in the State of Maryland and Korhonen's group E (Motta and Korhonen 1986). A definite connection was made between Korhonen's group C (*A. ostoyae*) and North American group I (Anderson and others 1980; Morrison and others 1985). Finally, a tentative connection was shown in Anderson and others' (1980) data between *A. bulbosa* and North American group VII and between *A. cepistipes* and North American group X.

These gains in clarifying the identity of *Armillaria* isolates are significant, but several points of confusion still exist. Most workers (Adams 1974; Kile 1981; Korhonen 1978; Shaw and Roth 1976) have limited their studies to rhizomorphic and fan collections from diseased plants or stumps in areas of obvious infection or, if collections covered a wider geographic area, they were limited to fruiting bodies (Anderson and Ullrich 1979; Morrison and others 1985). These sampling philosophies may provide a biased view of *Armillaria* because all populations do not fruit regularly and because potentially pathogenic populations can exist in a nonfruiting status on apparently healthy hosts. Korhonen (1978) concluded that clonal delineation of isolates in Finland by both vegetative and genetic means gave nearly identical results. In terms of clone size, both methods gave similar results in Western North America (Anderson and others 1979).

Effective management of forests where *Armillaria* is a potential threat requires the answers to several basic questions. Is risk uniform over a forested area or does it vary, and can it be predicted by applying certain criteria? Are all hosts at equal risk? If not why not? Do certain forest management actions increase the problem and others reduce it? Answers to these questions require knowledge about the distribution and behavior of the genotypes, ecotypes, and species of the causal organism over a large area. A study was conceived to answer some of these questions as they pertain to an area 600 miles in diameter, centered on Moscow, ID. Because our goal was to characterize the *Armillaria* population over the entire area, initial sampling was limited to vegetative structures. This paper reports the delineation of clones and their geographic and host range from *Armillaria* isolates sampled as vegetative structures on eighty-seven 0.04-hectare random plots located on 12 National Forests.

MATERIALS AND METHODS

Plot selection, plot location, and fungus isolation procedures were described previously (McDonald and others 1987). Contaminant-free isolates (individual pure cultures) of the genus were tested for compatibility without knowing the identity of the isolates (blind challenge test) in the following fashion: Up to six isolates were inoculated onto 3 percent malt extract agar (2 percent agar) in 50-mm plastic culture (petri) plates according to the pattern shown in figure 1. A 1-mm plug of each isolate was cut from the edge of an actively growing colony and placed 5 mm from its neighbor. All field isolates were presumed to

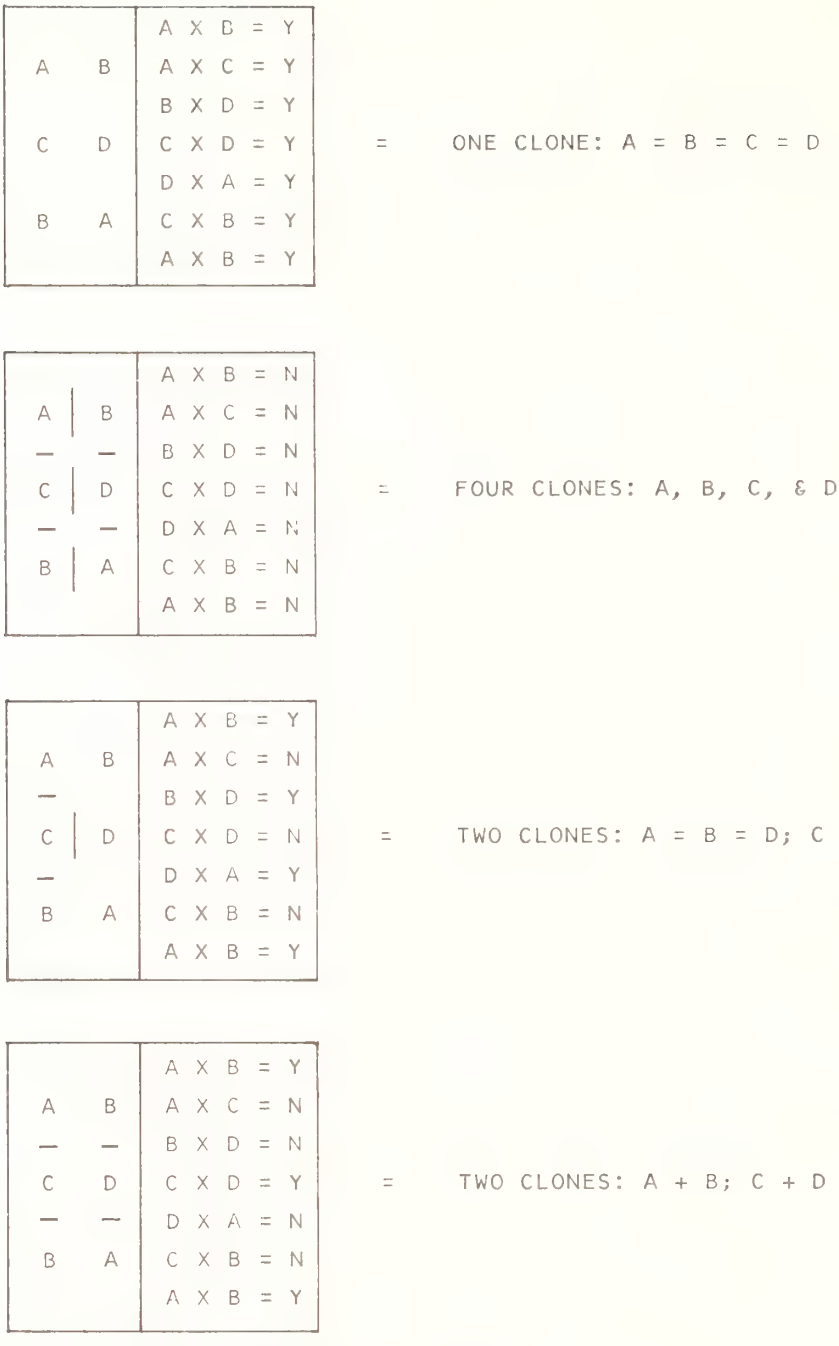


Figure 1—Sample illustrations of pattern of isolate challenges used to delineate clones of the genus *Armillaria* found on National Forests of the Northern Rocky Mountains.

be stable diploids (Korhonen 1978). The plates were incubated under room conditions for 21 to 30 days prior to reading and recording results. Each challenge was replicated three times to produce a single evaluation (read). Each of us independently assessed the three replications to record a summation of "yes" (compatible) or "no" (noncompatible). The three replications were judged "yes" if the challenge mates grew freely together and "no" if they failed to grow together, as shown by a line of demarcation, a free space, or a line resulting from mycelium crowding. A crowd line is formed when the challengers push against each other but appear not to join and they do not form a brown line of demarcation. Genetically identical mycelia are thought to freely grow together (Korhonen 1978). Relationships between isolates that failed to grow together could range from parents and sibs with identical compatibility alleles but otherwise different genomes to species that belong to different intersterility groups (Korhonen 1978).

PREMISE FOR CLONE DEFINITION

SAMPLE CHALLENGES OF 10 CULTURES FROM PLOT FH-4

1ST PREMISE CHALLENGE:	175 X	176	177	178	180	181	182	183	184	185	186
RESULT:		N	N	N	Y	Y	Y	N	Y	Y	N
REORDER:		180	181	182	184	185	176	177	178	183	186
RESULT:		Y	Y	Y	Y	Y	N	N	N	N	N

2ND PREMISE CHALLENGE:	176 X	177	178	183	186
RESULT:		N	Y	Y	N
REORDER:		178	183	177	186
RESULT:		Y	Y	N	N

3RD PREMISE CHALLENGE:	177 X	186
RESULT:		N

CONCLUSION: 4 CLONES PROVISIONALLY DEFINED

FH-41 = 175, 180, 181, 182, 184, 185
FH-42 = 176, 178, 183
FH-43 = 177
FH-44 = 186

Figure 2—Detailed premise analysis of challenge results obtained from vegetative isolates of the genus *Armillaria* found on 0.04-ha plot No. 4 located on the Flathead National Forest in Montana (FH-4).

The blind read was accomplished by working in three-person teams. One constructed the combinations of challenges and labeled (sequentially) each set of six isolates with a challenge number. The isolate numbers and associated challenge number were recorded, but their plot identification and other data were kept separated. The first round of challenges was accomplished over a period of 12 months, with individual challenges being repeated up to 10 times. These challenges were made in random combinations among the isolates from within a National Forest. Next, Punnett squares were constructed for all the isolates within each plot from within each National Forest. Blind challenges were then constructed to complete preliminary clonal definitions (premise-challenge) of the isolate populations from each plot (figs. 2, 3). Further blind challenges were made to complete the verification regions of each Punnett square (fig. 3). The evaluations by the two of us were recorded separately. Thus, each cell of the square could have a mixture of yes and no responses.

SAMPLE OF CLONAL-DEFINITION PUNNETT SQUARE: PLOT FH-4

CLONES	FH-41						FH-42			FH-43	FH-44
ISOLATES	175	180	181	182	184	185	176	178	183	177	186
PREMISE	*175*	*4Y*	*4Y*	*4Y*	*2Y*	*2Y*	*18N*	*3N1Y*	*12N*	*7N1Y*	*4N*

VERIFY	180	16Y	2Y	2Y	6Y	10N	6N2Y	3N1Y	4N	2N
		181	2Y	2Y	6Y	4N	4N	1N1Y	4N	6N
			182	2Y	2Y	4N	4N	13N1Y	4N	2N
				184	10Y	2N	2N	2N	2N	2N
					185	2N	2N	2N	4N	6N

PREMISE	*176*	*6Y*	*4Y*	*8N*	*2N*

VERIFY	178	22Y2N	26N2Y	2N
	183		15N1Y	2N

PREMISE	*177*	*4N*

Figure 3—Detailed premise and verification analysis of vegetative isolates of the genus *Armillaria* found on plot FH-4.

Given the total number of determinations in a plot and the pattern that developed, the observed number of yes and no responses was tested against the expected number (fig. 4). If the fit was statistically satisfactory, the provisional clonal delineation was accepted.

Behavior of each clone was assessed by its pattern of occurrence as saprophytic fans or epiphytic rhizomorphs on dead conifers, as parasitic fans or epiphytic rhizomorphs on *Armillaria*-infected or killed conifers, and as epiphytic rhizomorphs on apparently healthy hardwoods and conifers. Chi-square contingency tables with correction for continuity (Snedecor 1956) were used to test these relationships. Geographic range of individual clones within a National Forest was investigated by challenging randomly selected isolates within clones across plots within a National Forest.

RESULTS

Clone Definitions

Because it is impossible to present the complete analysis of 70 plots, we will discuss one plot in detail and summarize the rest. Plot 4 from the Flathead National Forest was selected because it included several clones, two of which were represented by multiple isolates. The premise-challenges (figs. 2, 3, and 4) clearly defined four clones. The verification-challenges clearly supported the definitions (plot FH-4 in table 10, appendix). Clone FH-41 (Flathead N.F.-plot 4, clone number 1) was present exclusively on *Armillaria*-killed or fading Douglas-fir (*Pseudotsuga menziesii*), Englemann spruce (*Picea engelmannii*), and subalpine fir (*Abies lasiocarpa*) as both mycelial fans and epiphytic rhizomorphs. Clone FH-42 was present as epiphytic rhizomorphs on healthy western larch (*Larix occidentalis*), Douglas-fir, and maple (*Acer* sp.). Clone FH-43 was present as epiphytic rhizomorphs on healthy willow (*Salix* sp.). Clone FH-44 was growing epiphytically on a healthy subalpine fir.

In total, 377 isolates from 70 plots were delineated into 160 clones. An additional 17 single-isolate plots were added to make the total 394 isolates, 177 clones, for 87 plots. Of the 70 plots supplying two or more isolates, two that were supporting five clones failed to yield acceptable clonal definitions (plots FH-6 in table 4 [see section The Challenges] and LO-2A in table 13, appendix). Thus, five of the 177 clones were not adequately defined and were removed from the data for the remaining analyses.

CHI-SQUARE GOODNESS-OF-FIT TEST FOR CLONAL
DELINEATION OF ISOLATES FROM PLOT: FH-4

PROVISIONAL DEFINITION

*COUNT NUMBER OF READS IN YES AND NO PORTIONS OF PREMISE LINES
*COUNT NUMBER OF NO READS IN YES PORTIONS
*COUNT NUMBER OF YES READS IN NO PORTIONS
*COMPUTE CHI-SQUARE

	YES REGION	NO REGION
NUMBER EXPECTED	26	60
NUMBER OBSERVED	26	58
DEVIATION	0	2
CHI-SQUARE	0/26 +	4/60 = 0.07

PROBABILITY OF LARGER CHI-SQUARE (1 df) = 0.50

*PROVISIONAL DEFINITION OF CLONE DELINEATION ACCEPTED

VERIFICATION OF CLONE DEFINITIONS

*COUNT NUMBER OF READS IN VERIFY REGIONS OF PUNNET SQUARE
*COUNT NUMBER OF NO READS IN YES REGIONS
*COUNT NUMBER OF YES READS IN NO REGIONS
*COMPUTE CHI-SQUARE

	YES REGION	NO REGION
NUMBER EXPECTED	74	150
NUMBER OBSERVED	72	148
DEVIATION	2	8
CHI-SQUARE	4/72 +	64/150 = 0.48

PROBABILITY OF A LARGER CHI-SQUARE (1 df) = 0.50

*PROVISIONAL CLONAL DEFINITION IS VERIFIED

Figure 4—Explanation of statistical analysis of data obtained from plot FH-4.

The Challenges

A total of 5,543 challenges were made in the course of delineating the population of isolates into clones. Because the blind challenges contained 192 isolate × self challenges, the precision of the methodology could be investigated. The challenges were classified into two groups where compatibility (yes) is expected (isolate × self and isolates within clones) and two groups where noncompatibility (no) is expected (clones in plots and plots × plots). Because they were expected to be identical, "yes" was expected any time an isolate was selfed. "Yes" was also expected when two isolates shown by previous tests to belong to the same clone were challenged (verifying region of the Punnett square). "No" was expected if two clones separated by more than 500 meters were challenged according to current ideas about clone extent in western forests (Anderson and others 1979). "No" was expected if two previously defined clones from the same plot were challenged. Two kinds of disagreement were investigated: the readers recorded independently and could disagree with each other, or they could agree (in the read) on the result of the challenge but disagree with the expected result. The selfed isolates provide a control or check on the challenge methodology because the only presumed source of variation is the challenge system. The readers disagreed 4 percent of the time when a "yes" was expected from selfed challenges. The population of reads obtained from the clone-verification zones of the Punnett squares was virtually the same as reading selfed isolates (table 1).

When "yes" was expected from blind reading of selfed isolates, the readers agreed to disagree with the expectation 5 percent of the time. The clone-verification population was not significantly different from the selfed isolates (table 2), even though the former population showed reduced disagreement.

Clones will fail to grow together because they belong to different intersterility groups or they are different genotypes within the same group. Thus the level of reader differences with a "no" expectation was assessed. Disagreement among readers was significantly different between clones within plots and clones between plots (table 3), yet the difference was not significant when readers agreed to disagree with expected results (table 4).

Geographic Extent of Clones

The geographic extent of clones within a National Forest was examined by constructing challenges of coded isolates, in all possible combinations of isolates, obtained from the 12 National Forests. The challenges between clones from different plots resulted in 95 percent "no," 2 percent "yes," and 3 percent "maybe" (table 5). The National Forests varied from 0 percent to 8 percent double "yes" when it was expected that both would be "no."

Table 1—Disagreement between two readers of challenges between field isolates of *Armillaria* when isolates were expected to be compatible

Isolate populations	Number of challenges			Reader disagreement
	Yes and no	Two yes	Total	
				Percent
Selfed	7	176	183	3.8
Clone verification	17	427	444	3.8

χ^2 = 0.05 Probability of larger χ^2 (1 df) = 0.90

Table 2—Accord in dissent with theoretical expectation between two readers of challenges between field isolates of *Armillaria* when isolates were expected to be compatible

Isolate populations	Number of challenges			Reader dissent
	Two no	Two yes	Total	
				Percent
Selfed	9	176	185	4.7
Clone verification	16	427	443	3.6

χ^2 = 0.26 Probability of larger χ^2 (1 df) = 0.70

Table 3—Disagreement between two readers of challenges between field isolates of *Armillaria* when isolates were expected to be incompatible (challenges from verify zone-no region of clone-definition Punnett squares and clones between plots)

Isolate populations	Number of challenges			Reader disagreement
	Yes and no	Two no	Total	
				Percent
Verify zones	25	426	451	5.5
Clones between plots	102	3,106	3,308	3.1

χ^2 = 4.00 Probability of larger χ^2 (1 df) = 0.05

Table 4—Accord in dissent with theoretical expectation between two readers of challenges between field isolates of *Armillaria* when isolates were expected to be incompatible (challenges from verify zone-no region of clone-definition Punnett squares and clones between plots)

Isolate populations	Number of challenges			Reader dissent
	Two yes	Two no	Total	
				Percent
Verify zones	17	426	443	3.8
Clones between plots	95	3,128	3,223	2.9

χ^2 = 0.76 Probability of larger χ^2 (1 df) = 0.40

Table 5—Percentage of disagreement between two readers and agreement to disagree with expectation when *Armillaria* isolates from clones from different plots within a National Forest are challenged

National Forest	Number of challenges	No	Yes	Yes and no
		- - - - - - - *Percent* - - - - - - -		
Coeur d' Alene	153	96	2	2
Colville	256	100	0	0
Clearwater	76	98	1	1
Flathead	264	93	3	4
Kaniksu	154	93	6	1
Kootenai	232	89	8	3
Lolo	240	94	6	0
Nez Perce	262	92	2	6
Payette	395	95	2	3
St. Joe	554	96	1	3
Umatilla	568	96	1	3
Wallowa-Whitman	129	93	7	0
Total	3,283	95	2	3

Table 6—Characteristics of *Armillaria* clones obtained from Northern Rocky Mountain National Forests

Clone source	Number of clones	Percent of clones	Isolates per clone
Hardwood shrubs	42	24	1.2
Healthy and detritus conifer	64	36	1.4
Shrubs and conifers	32	18	4.1
Free soil rhizomorph	4	2	1.0
Pathogenic on conifers	22	12	1.4
Shrubs and pathogenic on conifers	13	7	4.3
Total clones	177		

Number of Clones per Plot

The average number of clones per plot was 2.3. The average number of isolates per plot was 5.4. Plot SJ-1 (table 16, appendix) provided 12 isolates and three clones. A nearby plot, SJ-4 about 17 km northwest, gave the largest number of clones, which was six among eight isolates.

Clone Habits

The clones were classified according to their host affiliations (table 6). Six mutually exclusive classes were established. The first included clones existing as rhizomorphs epiphytic on apparently healthy hardwood brush. The second was epiphytic on healthy conifers, as well as conifer detritus. The third class included epiphytic rhizomorphs on both conifers and hardwoods. The fourth was composed of clones from rhizomorphs unattached to any organic material in the soil. The fifth included clones that were restricted to conifers and connected to conifer pathogenicity by having both fan isolates and epiphytic growth on conifers that were showing symptoms from the *Armillaria* infection. A sixth class contained clones connected, as above, to conifer pathogenicity but were also found in epiphytic associations with hardwoods.

There are several trends associated with clone habit. The highest percentage of clones was found on healthy hardwoods and on healthy conifers and/or conifer detritus. These tended to be represented as single isolates (table 6). Clones sampled as multiple isolates tended to be on a variety of host types (shrubs and conifers in table 6). Likewise, pathogenic clones that occurred on both shrubs and conifers tended to exist on a variety of substrates, but those present only as conifer pathogens tended to occur as single isolates.

DISCUSSION

Clone Definitions

The vegetative samples used in this study of *Armillaria* spp., as they exist in the Northern Rocky Mountains, separated into 177 separate and distinct clones. We have yet to directly determine their taxonomic affiliations and some other important traits. As a research resource they provide a sizable population of cultures with demonstrated genetic interrelationships that will provide a population on which to build a classification system based on traits as expressed in culture. This should be done on a large population before species relationships are known. As such, it would allow fair and unbiased determination of the stability of the traits. After a classification based on stable traits is developed, it can be verified by determination of the species of each clone.

Vegetative collections of *Armillaria* spp. are believed to be diploid, but the occurrence of haploids has not been studied. These clones will provide an ideal resource on which to study this possibility—for example, haploids can be distinguished by their fluffy aerial mycelium (Anderson and Ullrich 1979; Korhonen 1978), haploid nuclei can be separated from diploid nuclei by microspectrophotometric techniques and nuclear volume measurements (Motta 1985; Peabody and Peabody 1984), and finally, a vegetative isolate that is haploid would behave differently than a diploid in challenge and mating tests.

The Challenge System

Results reported in this paper demonstrate that the reading of isolate compatibility is not without ambiguity; however, our level of error is consistent with that reported by others. Within our population of isolates it appears that about 5 percent of the interpretations between closely related genotypes (tables 1 and 2) are subject to error. This level is less than the 10 percent error level reported for similar interactions within closely related genotypes of *A. luteobubalina* (Kile 1983). Matings between supposedly compatible haploids also yield 5 to 10 percent ambiguous interpretations (Kile 1983; Korhonen 1978). Placing numerous unrelated cultures in the same confined space apparently did not lead to unstable challenge results. The system of challenges for field diploid isolates, as used in this study, will give repeatable

results, and it provides a saving in time and resources compared to a single challenge per plate. The precision of our results reinforces the need to base clone delineation on repeated challenges of coded isolates.

The results of the expect-"no" analysis for both conditions (tables 3 and 4) can also be interpreted on the basis of ambiguous-separation between closely related genotypes. Both kinds of error indicate uncertain reads, and both kinds of errors are higher within plots than between plots. The interpretation of this pattern, however, is different than for the expect-"yes" case. An additional possible source of error in the expect-"no" case is the existence, in the field, of haploid vegetative isolates that could function as "testers." For example, where we use four isolates placed 5 mm apart within the same petri dish they could grow freely with any diploid of the same species and mating could occur, after which the haploid would not react with a different adjacent diploid clone. The existence of such haploids in a population believed to be diploid would generate unstable results, especially within the multiple isolate challenge system used by us. Some of these problems could be circumvented if mating reactions and mycelial growth pattern were also recorded; haploids produce a distinctive growth of aerial mycelium (Korhonen 1978; Ullrich and Anderson 1978).

As stated above, the verification system we present is predicated on the testing of diploid isolates. The existence of a haploid isolate would lead to inconclusive results. If two clones of the same species were being delineated, and one clone contained a haploid isolate, that haploid could grow with both clones. An unexpected "yes" reading would result. The same problem exists in testing the wider extent of clones. According to current theory, a haploid isolate could conceivably give a "yes" read against any diploid isolate of the same species from anywhere in the world. If one were expecting such a mating response, this situation could be monitored. At the very least, any future clonal delineation should include provisions for assessing mating and the presence of haploids in the test population. The existence of haploid isolates could explain the unusually high number of ambiguous readings between plot-to-plot clones within a National Forest (table 5). These challenges were made on an isolate-specific level before the clones were defined to provide data unbiased by reader knowledge. This system led to a random selection of isolate pairing. If a haploid was selected to represent the clone and it was paired against the same species from a distant plot, a "yes" (when a "no" was expected) would result. Even though most authors believe that vegetative field isolates are diploid (Kile 1983; Korhonen 1978; Ullrich and Anderson 1978; Wargo and Shaw 1985), one must keep in mind that most of these workers have made almost exclusive use of cultures derived from sporophores or from vegetative samples obtained in the vicinity of sporophores on sites where *Armillaria* spp. are in a pathogenic mode. In addition, it is theoretically possible that haploids could have arisen from diploids unstable in culture. This, however, does not appear to be the case, since the diploids of the genus have been shown to possess a high degree of genetic stability (Anderson and Ullrich 1982). Existence of these haploids may not be so surprising in light of the recent reports of haploid tissues in *Armillaria* spp. basidiocarps (Peabody and Peabody 1986). Our tentative conclusion based on the challenge behavior of some isolates is that our random samples of vegetative structures most probably included some haploids. A thorough understanding of the confirmed existence, distribution, behavior, and role of such haploid components would explain much about the genetics and epidemiology of the genus *Armillaria*.

Number of Clones per Plot

A most interesting finding is that an average of 2.3 clones per 0.04-ha plot was found. This result supports the current ideas regarding the distribution of clones and species. As seen in tables 7 thru 18 in the appendix, most plots contained one or two clones regardless of the number of isolates obtained. This argues for the coexistence of two species on most sites, since others have not found two clones of the same species to commonly coexist (Kile 1983; Korhonen 1978; Ullrich and Anderson 1978). Several sites had three clones and could represent the coexistence of three species. The final answer to this generalization will come with the confirmation of species affiliations of the sampled clones.

Clone Habits

Associations of clones by hosts and rhizomorph production (table 6) suggest four *Armillaria* spp. in our population of randomly collected isolates. One group of clones comprised 24 percent of all clones and was restricted to hardwood shrubs. These were generally found as a single rhizomorphic isolate. If the average number of rhizomorphic-derived cultures is a measure of tendency of a clone to produce rhizomorphs, then this group may signify a species that rarely produces rhizomorphs and is restricted to hardwood hosts. A second group was restricted to conifers and produced few rhizomorphs. It averaged 1.4 isolates per clone. This group was about evenly split on healthy conifers, conifer detritus, and in pathogenic mode. It included 48 percent of all clones. This pattern fits *A. ostoyae* as described by Rishbeth (1982) in England and Morrison and others (1985) in British Columbia. The third group produced an average of 4.1 isolates per clone. It was found on shrub detritus, conifer detritus, healthy shrubs, and healthy conifers. This group contained 18 percent of all clones and behaves like *A. bulbosa* in England (Rishbeth 1982) where it was found on both hardwoods and conifers. This species is a prolific producer of rhizomorphs, and is not pathogenic. This species was found in British Columbia but was restricted to hardwoods as shown by a sporophore population (Morrison and others 1985). The fourth group of clones was a prolific producer of rhizomorphs (4.3 isolates per clone) and occurred on shrubs, conifer detritus, healthy conifers, and in a pathogenic mode. Only 7 percent of the clones belonged to this group. This group may represent a species that produces many rhizomorphs, is pathogenic on conifers, and commonly exists in a saprophytic mode.

CONCLUSIONS

A population of clones belonging to the genus *Armillaria* has been defined. All isolates comprising the clones are secured in contaminant-free archival collections. An effective technique of challenging large numbers of isolates to delineate clones has been demonstrated and verified. Grouping of clones, based on the behavior of certain species, suggests the Northern Rockies is home for at least four species of the genus. Many avenues appear to be open for the confirmation of species affiliation in populations of vegetative isolates. Complete understanding of the life cycle, genetics, and ecological role of the *Armillaria* complex will come with a thorough investigation of vegetative populations obtained from healthy as well as diseased stands.

REFERENCES

Adams, D. H. 1974. Identification of clones of *Armillaria mellea* in young-growth ponderosa pine. Northwest Science. 48: 21-28.

Anderson, J. B. 1986. Biological species of *Armillaria mellea* in North America: redesignation of groups IV and VIII and enumeration of voucher strains for other groups. Mycologia. 78: 837-839.

Anderson, J. B.; Korhonen, K.; Ullrich, R. C. 1980. Relationships between European and North American biological species of *Armillaria mellea*. Experimental Mycology. 4: 87-95.

Anderson, J. B.; Ullrich, R. C. 1979. Biological species of *Armillaria mellea* in North America. Mycologia. 71: 402-414.

Anderson, J. B.; Ullrich R. C. 1982. Diploids of *Armillaria mellea*: synthesis, stability, and mating behavior. Canadian Journal of Botany. 60: 432-439.

Anderson, J. B.; Ullrich, R. C.; Roth, L. F.; Filip, G. M. 1979. Genetic identification of clones of *Armillaria mellea* in coniferous forests in Washington. Phytopathology. 69: 1109-1111.

Kile, G. A. 1981. *Armillaria luteobubaline*: a primary cause of decline and death of trees in mixed species Eucalypt forests in central Victoria. Australian Forest Research. 11: 63-77.

Kile, G. A. 1983. Identification of genotypes and the clonal development of *Armillaria luteobubalina* Watling & Kile in Eucalypt forests. Australian Journal of Botany. 31: 657-71.

Korhonen, K. 1978. Interfertility and clonal size in the *Armillaria mellea* complex. Karstenia. 18: 31-42.

McDonald, G. I.; Martin, N. E.; Harvey, A. E. 1987. Occurrence of *Armillaria* spp. in forests of the Northern Rocky Mountains. Res. Pap. INT-381. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 7 p.

Morrison, D. J.; Chu, D.; Johnson, A. L. S. 1985. Species of *Armillaria* in British Columbia. Canadian Journal of Plant Pathology. 7: 242-246.

Motta, J. J. 1985. Evidence for significant difference in nuclear DNA content between two geographically isolated clones of *Armillaria mellea*. American Journal of Botany. 72: 1307-1310.

Motta, J. J.; Korhonen, K. 1986. A note on *Armillaria mellea* and *Armillaria bulbosa* from the middle Atlantic States. Mycologia. 78: 471-474.

Peabody, D. C.; Peabody, R. B. 1984. Microspectrophotometric nuclear cycle analysis of *Armillaria mellea*. Experimental Mycology. 8: 161-169.

Peabody, R. B.; Peabody, D. C. 1986. Haploid monokaryotic basidiocarp tissues in fine members of the *Armillaria* complex. Mycological Society of America Newsletter. 37: 38.

Rishbeth, J. 1982. Species of *Armillaria* in southern England. Plant Pathology. 31: 9-17.

Roll-Hansen, F. 1985. The *Armillaria* species in Europe. European Journal of Forest Pathology. 15: 22-31.

Shaw, C. G., III; Roth, L. F. 1976. Persistence and distribution of a clone of *Armillaria mellea* in a ponderosa pine forest. Phytopathology. 66: 1210-1213.

Snedecor, G. W. 1956. Statistical methods. Ames, IA: Iowa State University Press. 534 p.

Ullrich, R. C.; Anderson, J. B. 1978. Sex and diploidia in *Armillaria mellea*. Experimental Mycology. 2: 119-129.

Wargo, P. M. 1984. How stress predisposes trees to attack by *Armillaria mellea*—a hypothesis. In: Kile, G. A., ed. Proceedings of the sixth international conference on root and butt rots of forest trees. CSIRO Melbourne: 115-121.

Wargo, P. M.; Shaw, C. G., III. 1985. *Armillaria* root rot: the puzzle is being solved. Plant Disease. 69: 826-832.

APPENDIX: DELINEATION INTO CLONES OF *ARMILLARIA* SPP. ISOLATES COLLECTED ON 12 NATIONAL FORESTS

Table 7—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Coeur d' Alene National Forest in Idaho

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
CD-1	8	7	3	18	16	22	20	0.40	12	12	20	20	0.00
CD-2	7	5	2	10	10	2	2	.00	8	8	12	12	.00
CD-3	7	3	2	6	6	4	4	.00	0	0	8	8	FIT[1]
CD-4	8	5	2	14	14	2	2	.00	22	20	12	11	.27
CD-5	9	1	1	—	—	—	—	—	—	—	—	—	—
CD-6	2	0	—	—	—	—	—	—	—	—	—	—	—
CD-7	1	0	—	—	—	—	—	—	—	—	—	—	—
CD-7a	4	4	2	8	8	8	8	.00	4	4	6	6	.00
CD-8	7	0	—	—	—	—	—	—	—	—	—	—	—
Plot $\bar{X}$	5.9	2.8	2.0										

[1]Close or exact fit not testable by chi square.

Table 8—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Colville National Forest in Washington

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
CO-1H	6	5	3	14	14	16	16	0.00	0	0	10	10	FIT[1]
CO-1	6	6	3	12	12	30	26	1.20	10	10	28	28	0.00
CO-2	1	1	1	—	—	—	—	—	—	—	—	—	—
CO-3	7	6	1	32	32	0	0	FIT	44	44	0	0	FIT
CO-4	4	4	3	2	2	14	14	.00	0	0	8	8	FIT
CO-5	4	4	2	4	4	8	6	.50	4	2	4	4	1.00
CO-6	0	—	—	—	—	—	—	—	—	—	—	—	—
CO-7	9	8	1	30	30	0	0	FIT	74	74	0	0	FIT
CO-8	10	9	3	36	25	26	21	4.32	54	52	36	29	1.44
Plot $\bar{X}$	5.9	5.4	2.1										

[1]Exact fit not testable by chi square.

Table 9—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Clearwater National Forest in Idaho

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
CW-1	7	7	1	22	22	0	0	FIT[1]	50	50	0	0	FIT
CW-2	6	0	—	—	—	—	—	—	—	—	—	—	—
CW-3	6	0	—	—	—	—	—	—	—	—	—	—	—
CW-4	6	0	—	—	—	—	—	—	—	—	—	—	—
CW-5	7	5	2	8	8	4	4	0.00	8	8	12	12	0.00
CW-6	2	2	1	4	4	0	0	FIT	—	—	—	—	—
CW-7	7	3	3	0	0	10	9	FIT	—	—	—	—	—
CW-8	7	1	1	—	—	—	—	—	—	—	—	—	—
Plot $\bar{X}$	6.0	2.3	1.6										

[1]Close or exact fit not testable by chi square.

Table 10—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Flathead National Forest in Montana

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
FH-1	0	—	—	—	—	—	—	—	—	—	—	—	—
FH-2	0	—	—	—	—	—	—	—	—	—	—	—	—
FH-3	5	1	1	—	—	—	—	—	—	—	—	—	—
FH-4	12	11	4	26	26	60	58	0.07	74	72	150	142	0.48
FH-5	10	6	3	28	28	14	14	.00	18	18	58	58	.00
FH-6	9	7	3	52	40	32	19	8.05	52	33	72	51	13.07
FH-7	6	5	5	0	0	74	60	FIT[1]	—	—	—	—	—
FH-8	2	0	—	—	—	—	—	—	—	—	—	—	—
Plot $\bar{X}$	7.3	5.0	3.2										

[1]Close or exact fit not testable by chi square.

Table 11—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Kaniksu National Forest in Idaho

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
KN-1	3	3	1	6	6	0	0	FIT[1]	2	2	0	0	FIT
KN-1A	2	2	2	0	0	4	4	FIT	—	—	—	—	—
KN-2	2	2	1	10	10	0	0	FIT	—	—	—	—	—
KN-3	7	7	3	12	8	16	16	1.33	22	22	26	26	0.00
KN-4	10	10	3	10	10	24	20	.67	30	30	46	37	1.76
KN-5	7	7	2	14	14	4	3	.25	26	26	22	22	.00
KN-6	0	—	—	—	—	—	—	—	—	—	—	—	—
KN-7	1	0	—	—	—	—	—	—	—	—	—	—	—
KN-8	6	6	2	16	16	6	4	.67	18	16	16	13	.78
Plot $\bar{X}$	4.8	4.6	2.0										

[1]Exact fit not testable by chi square.

Table 12—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Kootenai National Forest in Montana

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
KT-1	5	4	1	12	12	0	0	FIT[1]	8	8	0	0	FIT
KT-2	6	5	2	8	8	2	2	0.00	10	10	26	22	0.61
KT-3	8	8	5	12	12	68	60	.94	2	2	48	46	.80
KT-4	5	5	1	12	11	0	0	FIT	24	23	0	0	FIT
KT-5	3	2	1	6	6	0	0	FIT	—	—	—	—	—
KT-6	0	0	0	—	—	—	—	—	—	—	—	—	—
KT-6A	2	2	1	4	4	0	0	FIT	—	—	—	—	—
KT-7	6	5	3	6	6	26	18	2.46	2	2	18	13	1.39
KT-8	0	—	—	—	—	—	—	—	—	—	—	—	—
KT-8A	—	—	—	—	—	—	—	—	—	—	—	—	—
Plot $\bar{X}$	3.5	4.4	2.0										

[1]Close or exact fit not testable by chi square.

Table 13—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Lolo National Forest in Montana

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
LO-1	3	0	—	—	—	—	—	—	—	—	—	—	—
LO-2	—	—	—	—	—	—	—	—	—	—	—	—	—
LO-2A	9	9	2	18	18	4	4	0.00	18	18	14	7	2.33
LO-3	—	—	—	—	—	—	—	—	—	—	—	—	—
LO-3A	13	7	1	18	16	0	0	FIT[1]	24	24	0	0	FIT
LO-4	7	4	2	4	4	8	8	.00	0	0	4	2	FIT
LO-5	7	6	3	6	6	8	8	.00	8	6	24	22	.67
LO-6	3	3	3	0	0	12	12	FIT	—	—	—	—	—
LO-7	7	4	2	6	6	4	4	.00	2	2	2	2	.00
LO-8	7	7	3	12	12	8	8	.00	28	24	18	16	.79
Plot $\bar{X}$	5.6	5.0	2.3										

[1]Close or exact fit not testable by chi square.

Table 14—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Nez Perce National Forest in Idaho

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
NP-1	7	7	1	16	16	0	0	FIT[1]	24	24	0	0	FIT
NP-2	4	2	2	0	0	6	6	FIT	—	—	—	—	
NP-3	6	4	2	6	6	6	6	0.00	2	2	4	4	0.00
NP-4	7	6	1	12	12	0	0	FIT	28	28	0	0	FIT
NP-5	6	6	2	14	12	8	8	.29	10	10	26	26	.00
NP-6	9	6	4	8	8	8	8	.00	2	2	18	14	.89
NP-7	5	3	1	12	12	0	0	FIT	—	—	—	—	
NP-8	7	3	2	6	6	2	2	.00	0	0	6	6	FIT
Plot $\bar{X}$	6.4	4.6	1.9										

[1]Exact fit not testable by chi square.

Table 15—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Payette National Forest in Idaho

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
PA-1	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-1-7	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-1B	8	4	2	4	4	6	6	0.00	0	0	8	8	FIT[1]
PA-2	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-3	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-4	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-5	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-6	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-7	0	—	—	—	—	—	—	—	—	—	—	—	—
PA-7A	8	5	2	10	10	4	4	.00	8	8	10	10	.00
PA-8	4	0	—	—	—	—	—	—	—	—	—	—	—
PA-8A	13	8	3	12	12	12	12	.00	24	24	30	30	.00
Plot $\bar{X}$	3.0	4.25	2.3										

[1]Exact fit not testable by chi square.

Table 16—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the St. Joe National Forest in Idaho

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
SJ-1	14	12	3	14	14	10	10	0.00	62	51	78	71	2.59
SJ-2	9	4	1	26	23	0	0	FIT[1]	16	12	0	0	FIT
SJ-2A	3	3	1	10	10	0	0	FIT	4	4	0	0	FIT
SJ-3	9	6	3	6	6	18	18	.00	2	2	14	10	1.14
SJ-4	9	8	6	14	12	70	68	.34	0	0	66	57	FIT
SJ-5	7	0	—	—	—	—	—	—	—	—	—	—	—
SJ-6	0	—	—	—	—	—	—	—	—	—	—	—	—
SJ-7	7	4	2	12	12	6	6	.00	2	2	10	10	.00
SJ-8	8	7	4	10	10	58	58	.00	12	10	14	14	1.33
Plot $\bar{X}$	7.3	5.5	2.9										

[1]Close or exact fit not testable by chi square.

Table 17—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Umatilla National Forest in Oregon and Washington

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
UM-1	2	2	2	0	0	8	6	FIT[1]	—	—	—	—	
UM-1A	4	4	2	4	4	2	2	0.00	4	4	4	4	0.00
UM-2	4	1	—	—	—	—	—	—	—	—	—	—	—
UM-3	0	—	—	—	—	—	—	—	—	—	—	—	—
UM-4	6	6	3	18	18	8	8	.00	10	10	10	8	.40
UM-5	4	3	1	18	18	0	0	FIT	6	5	0	0	FIT
UM-6	6	5	3	12	11	10	10	.08	0	0	12	12	FIT
UM-7	7	6	4	14	14	32	30	.13	8	8	26	25	.04
UM-8	10	10	2	20	18	4	4	.20	26	23	26	26	.35
Plot $\bar{X}$	4.8	4.6	2.4										

[1]Close or exact fit not testable by chi square.

Table 18—Delineation into clones of vegetative samples of *Armillaria* spp. collected on the Wallowa-Whitman National Forest in Oregon

National Forest	Number samples	Number isolates	Number clones	Provisional					Verification				
				Yes		No		Chi square	Yes		No		Chi square
				E	O	E	O		E	O	E	O	
WW-1	0	—	—	—	—	—	—	—	—	—	—	—	—
WW-2	5	4	1	12	12	0	0	FIT[1]	6	6	0	0	FIT
WW-3	5	5	2	6	6	6	6	0.00	4	4	10	10	0.00
WW-4	8	6	2	12	12	6	6	.00	34	30	10	10	.48
WW-5	9	8	4	14	14	28	28	.00	2	2	28	24	.57
WW-6	0	—	—	—	—	—	—	—	—	—	—	—	—
WW-7	0	—	—	—	—	—	—	—	—	—	—	—	—
WW-8	0	—	—	—	—	—	—	—	—	—	—	—	—
Plot $\bar{X}$	3.4	5.8	2.3										

[1]Exact fit not testable by chi square.

McDonald, Geral I.; Martin, Neil E. 1988. *Armillaria* in the Northern Rockies: delineation of isolates into clones. Res. Pap. INT-385. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 13 p.

Isolates derived from *Armillaria* spp. rhizomorphs and fans collected within a 300-mile radius of Moscow, ID, were delineated into clones. The 394 isolates taken from 87 randomly located 0.04-ha plots were assigned to 177 clones. Multiple blind assessments of isolates among clones produced an overall reading error of about 5 percent. An average of 5.4 isolates per plot yielded two to three clones per plot, leading to the conclusion that most plots supported two or three species of *Armillaria*. The clones seemed to fall into four groups with regard to host affinities, pathogenicity, and rhizomorph production. This suggests that the Northern Rocky Mountains are home to four *Armillaria* spp.

KEYWORDS: isolate compatibility, *Armillaria* specification, statistical analysis of clone definitions

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho
Bozeman, Montana (in cooperation with Montana State University)
Logan, Utah (in cooperation with Utah State University)
Missoula, Montana (in cooperation with the University of Montana)
Moscow, Idaho (in cooperation with the University of Idaho)
Ogden, Utah
Provo, Utah (in cooperation with Brigham Young University)
Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-386

Susceptibility of Ponderosa Pine to the Needle Cast Fungus *Lophodermium baculiferum*

R. J. Hoff

CLEMSON UNIVERSITY
MAY 18 1988
DOCUMENTS

THE AUTHOR

R. J. HOFF is principal plant geneticist with the Intermountain Research Station's Forestry Sciences Laboratory in Moscow, ID. He received a B.A. degree in biology from Western Washington State University and a Ph.D in botany from Washington State University.

RESEARCH SUMMARY

In 1985 a needle cast caused by *Lophodermium baculiferum* Mayr severely infected a provenance test and a progeny test of ponderosa pine located in northern Idaho. Populations of ponderosa pine from northern Idaho-northeastern Washington and western Montana differed in their susceptibility to needle cast. Geographic area accounted for most of the variation among populations; elevation accounted for very little. The populations in the north-central portion of the collection area were most resistant, and these were connected with the more susceptible southern populations by gentle clines. Family heritability was 0.60; for individuals it was 0.45.

February 1988

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Susceptibility of Ponderosa Pine to the Needle Cast Fungus *Lophodermium baculiferum*

R. J. Hoff

INTRODUCTION

In 1983, a small amount of needle cast was observed in a plantation of ponderosa pine (*Pinus ponderosa* Laws.) in northern Idaho. In 1984, the level of damaged needles had increased, and by 1985 the damage had become severe. The causal organism (*Lophodermium baculiferum* Mayr) was identified by Sue Hagle, USDA Forest Service, Northern Region, Forest Pest Management, and John M. Staley, Department of Pathology, Washington State University.

Needle cast fungi can substantially decrease growth and can also cause mortality, especially if the infection is of current year's needles. Scots (*Pinus sylvestris* L.) pine stands of central Europe have sustained heavy losses due to *L. pinastri* (probably *L. seditiosum*) (Squillace and others 1975). In North America the same fungus causes downgrading and mortality of Scots pine (Merrill and Kistler 1976; Skilling 1975; Skilling and Nicholls 1971). Transfer of seed of populations of Scots pine with differing levels of susceptibility to *L. pinastri* (probably *L. seditiosum*) has compounded this disease problem (Scholz and Stevens 1982; Squillace and others 1975).

The infection process or infection needs of *L. baculiferum* are not known; neither is there any knowledge concerning the genetics of resistance of ponderosa pine to infection by this needle cast. However, data on and evidence of resistance have been observed for several other needle cast fungi. For example, Harvey (1976) observed uninfected individuals within a provenance test of ponderosa pine that were heavily infected with *Lophodermella morbida* Staley & Bynum. Mitchell and others (1976) reported resistant trees within a plantation of Corsican pine (*Pinus nigra* var. *maritinea* [Acton] Melville) infected by *Lophodermella sulcigena* (Rostr.) v. Hohn. Hoff (1985) reported that the degree of susceptibility of lodgepole pine (*Pinus contorta* Dougl.) infected with *Lophodermella concolor* (Dearn.) Darker was closely associated with elevation of the seed collection; within-family variability was also fairly high, yielding a family heritability of 0.73.

Conclusions from the large amount of literature on resistance of Scots pine to *Lophodermium* needle casts indicate that provenances differ in their response to infection (Baumanis and others 1982; Martinsson 1979), and there is a relatively high within-provenance and within-family variance for resistance (Martinsson 1979; Squillace and others 1975).

The purpose of this paper is to document the patterns of variation of infection caused by *L. baculiferum* on ponderosa pine with respect to geographic area and elevation and to document family variation.

MATERIALS AND METHODS

The Inland Empire Tree Improvement Cooperative has established several plantations of ponderosa pine in northern Idaho and western Montana. Trees in two plantations—one a provenance test, the other a progeny test—exhibited severe infection by *L. baculiferum* in 1985. Infection appeared uniformly heavy over the entire plantation, but there were scattered individuals throughout both tests that were not infected. These were often surrounded by severely infected trees.

The two tests were planted side by side during spring 1974 at the Lone Mountain tree improvement site 25 miles (40 km) north of Coeur d' Alene, ID, by the Northern Region of the Forest Service. The site is flat, with only slight undulations, at an elevation of 2,488 ft (758 m). The entire 160-acre (65-ha) site is surrounded by naturally regenerated ponderosa pine and lodgepole pine with a lesser mixture of grand fir (*Abies grandis* [Dougl.] Lindl.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), and western larch (*Larix occidentalis* Nutt.). This natural stand is two-layered with the overstory composed of mature scattered trees (remnants of harvest) and the lower layer composed of pole-sized trees 20 to 30 ft (6 to 9 m) tall. Most of these natural ponderosa pine were infected with *L. baculiferum* to some degree.

Provenance Test

The seed came from 92 stands (populations) in northeastern Washington, north of the Salmon River in Idaho, and western Montana (fig. 1). Open-pollinated seed was collected from five individuals per stand and combined.

The seedlings were grown at a Forest Service nursery near Coeur d'Alene, ID, in nursery beds for 2 years, then lifted and planted at the Lone Mountain tree improvement site in April 1974. The experimental design was a randomized complete block with 10 replications (blocks). Four progeny of each stand were planted per replication as a four-tree row plot.

Data were taken by viewing the needles (those produced in 1983) when the maximum expression of symptoms was evident, from mid-May to mid-June of 1985. The damage was evident as straw- to brown-colored needles. It was assumed that the amount of this damage reflected infection severity. First, the entire plantation was observed for 20 to 30 minutes to get an idea of the general level and range of infection. Then observers walked slowly along a row of trees and placed each tree in one of the following categories:

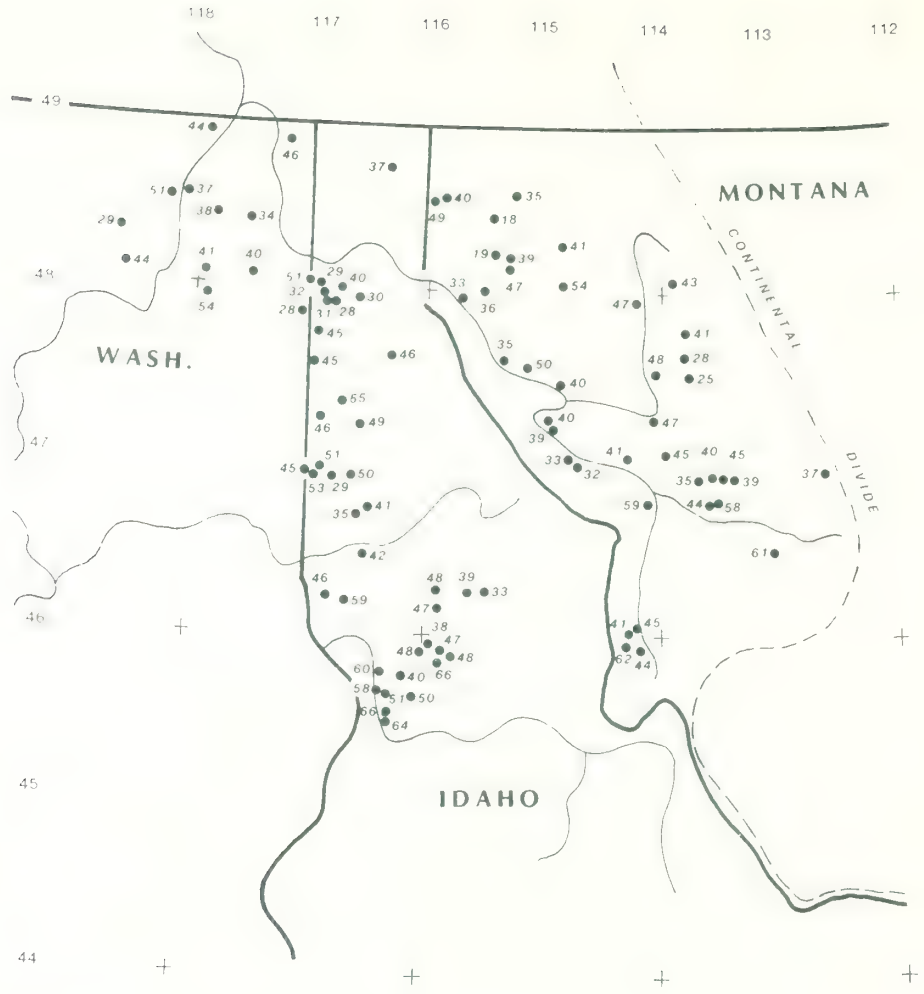


Figure 1—Actual levels of infection (percentage) by *Lophodermium baculiferum* for populations of ponderosa pine.

0 = no needle tissue infected

1 = less than 5 percent of needle tissue infected

2 = from 6 to 36 percent of needle tissue infected

3 = from 37 to 69 percent of needle tissue infected

4 = more than 70 percent of needle tissue infected.

Before analysis, the five categories were changed to the mean proportion of each class, that is: 1 = 0.025; 2 = 0.21; 3 = 0.53; and 4 = 0.85. For computing purposes, 0 = 0.0004.

An analysis of variance was used to determine significant differences among stands. Multiple regression analyses were used to relate the degree of infection to elevation and geographic location of the seed source. Independent variables included elevation, latitude, longitude, northwest-southeast coordinates, southwest-northeast coordinates, and their squares. The northwest-southeast coordinates equaled latitude × longitude and the southwest-northeast coordinates equaled (1/latitude) × longitude. The geographic variables were nested within two geographic regions: Idaho north of the Salmon River and Montana west of the Continental Divide (Rehfeldt 1980; Rehfeldt and Wykoff 1981). A stepwise multiple regression procedure for maximizing R^2 (SAS 1982) was completed.

Predicted infection values for geographic areas were produced using the best fit multiple regression equation for a constant elevation. Contour lines (isopleths) separating statistically equal levels of infection were determined by using the least significant difference formula (Steel and Torrie 1960) at a t-value of 0.2. The effect of elevation was determined by using the regression coefficients for the elevation factors of the multiple regression equation to predict infection values for a geographic intercept.

Progeny Test

Open-pollinated seed from 234 families was collected from 48 stands in northeastern Washington and Idaho north of the Salmon River. (Seed from these 48 stands was also included in the provenance test described above.)

The seedlings were grown as described for the provenance test. The experimental design was a randomized complete block design but with five replications (blocks). Four progeny from each family were planted as a four-tree row plot.

Table 1—Model for analysis of variance and expected mean squares

Source of variation	df[1]	Expected mean squares
Block	4	$\sigma^2_W + p\sigma^2_E + pfo^2_B$
Stand	47	$\sigma^2_W + p\sigma^2_E + pbo^2_{FS} + pf^* bo^2_S$
Family in stand	188	$\sigma^2_W + p\sigma^2_E + po^2_{FS}$
Experimental error	892	$\sigma^2_W + p\sigma^2_E$
Within plot	2,644	σ^2_W

Where: b = 5, S = 48, f = 234, f^* = 4.8 harmonic mean of families in stands; p = 3.01 harmonic mean of individuals within plots.

[1]Degrees of freedom were reduced by 44 for missing plots.

Data were taken as described for the provenance test. Table 1 shows the analysis of variance and expected mean squares. Heritability was calculated using the following formula:

For individual

$$h^2_I = \frac{4\sigma^2_{FS}}{\sigma^2_{FS} + \sigma^2_W}$$

For family

$$h^2_F = \frac{\sigma^2_{FS}}{\sigma^2_{FS} + \frac{\sigma^2_W}{pb} + \frac{\sigma^2_E}{b}}$$

where h^2_I = heritability based on individuals, h^2_F = heritability based on families, $4\sigma^2_{F/S}$ is the estimated additive variance for individuals, $\sigma^2_{F/S}$ for families, and σ^2_W, σ^2_E, pb, and b are defined in table 1.

Relationship of infection and the 1985 height was determined by regression analysis using the GLM procedure (SAS 1982).

RESULTS

Provenance Test

The level of infection by *L. baculiferum* varied from none (1 percent of the trees) to almost complete defoliation of 1983 needles (22.1 percent of the trees). Table 2 summarizes the amount of infection for both tests. Figure 1 shows the actual percentage of damage for each stand.

Analysis of variance of the levels of infection demonstrated that differentiation among stands for infection was highly significant (table 3).

Regression coefficients for the multiple regression equation that produced the best fit are listed in table 4. These resulted in an R^2 of 0.37, a mean square of 0.0386 with 9 degrees of freedom, and an error mean square of 0.0072 with 82 degrees of freedom, resulting in an F value of 5.4, significant at 1 percent level of significance.

Predicted values from the multiple regression equation at the mean elevation of all stands—3,282 ft (1,000 m)—are shown in figure 2. The center line represents the average predicted value, and lines depicting ±1/2LSD from this mean at the 0.2 level of significance were drawn north and south from this line.

Table 2—Level of infection (percent) by *Lophodermium baculiferum* on 2-year-old foliage of ponderosa pine by category

	Amount of foliage damaged		Test trees	
Category	Mean	Range	Provenance	Progeny
0	0	0	<1	<1
1	2.5	<5	7.4	4.8
2	21.0	6-36	36.3	34.2
3	53.0	37-69	34.2	32.8
4	85.0	>70	22.1	28.1

Table 3—Analysis of variance of infection by *Lophodermium baculiferum* on ponderosa pine

Source of variance	df[1]	Mean square	F
Block	9	0.136	
Stand	81	.103**	3.32
Block × stand	783	.031	

[1]Degrees of freedom were reduced by 36 for missing plots.
**Significant at the 1 percent level of probability.

Table 4—Intercept and regression coefficients from the best fit multiple regression equation for infection of ponderosa pine by *Lophodermium baculiferum*

Factor	*b* value
Intercept	−247.86612619
Elevation	−.00008780
Elevation^2	.00000001
Northwest	.01251327
Southwest zone 1	.00678625
Latitude	−1.44985788
Longitude	4.99039460
Longitude zone 1	.49234995
Longitude^2	−.02442355
(Southwest zone 1)^2	3.30576505

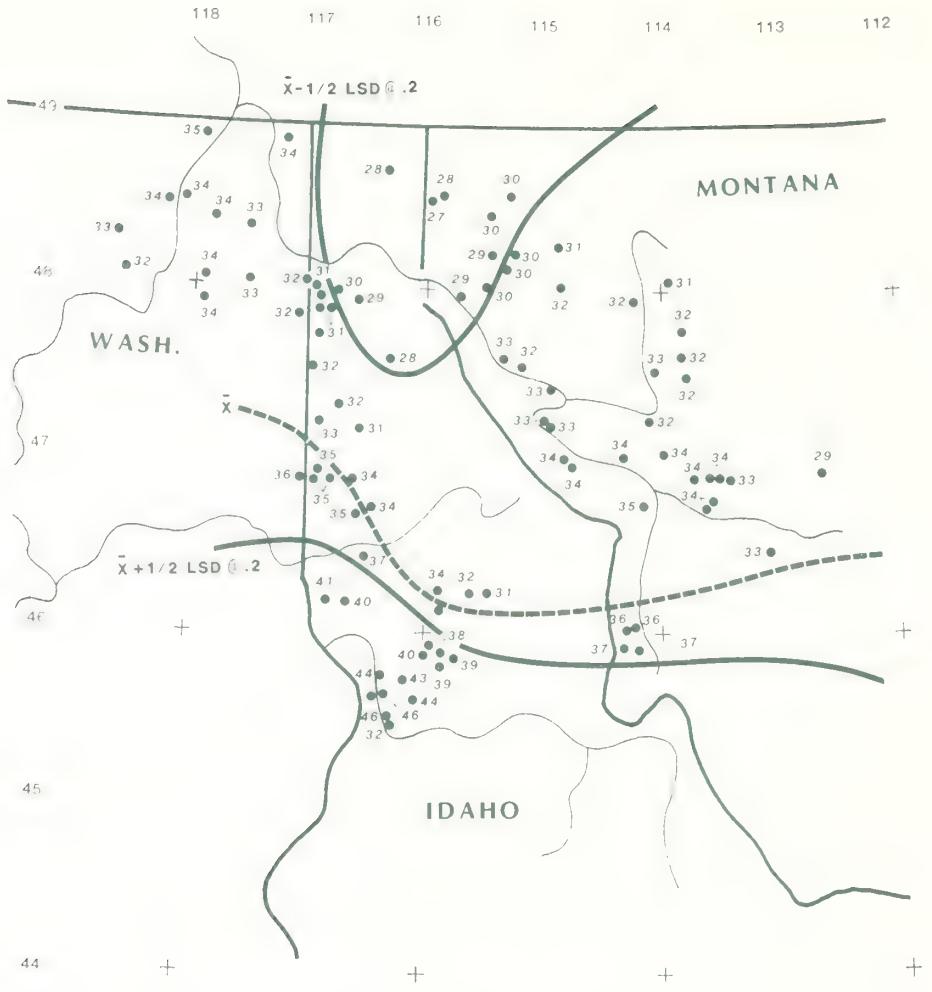


Figure 2—Predicted levels of infection (percentage) by *Lophodermium baculiferum* for populations of ponderosa pine derived from regression coefficients listed in table 4 at a constant elevation (mean of all stands, 3,282).

Elevation had no effect, as shown in figure 3. The plotted values are the actual percentages of infection plotted against elevation. The line (A) represents the predicted infection level at the southern geographic point using 44 percent for the collection area. The line was derived by using the regression coefficients for the elevation factors listed in table 4.

Progeny Test

The level of infection varied from none (1 percent of the trees) to nearly complete defoliation of 1983 needles (28.1 percent of the trees). The levels of infection are summarized in table 2.

Analysis of variance of the levels of infection shows that the differences among stands and families within stands were highly significant (table 5). Table 6 lists variance components. Heritability based on individuals was 0.45; for families, 0.60.

There was little relationship between the degree of infection and the heights of the trees in 1985 (fig. 4). The R^2 for populations was 0.02 and for families, 0.07.

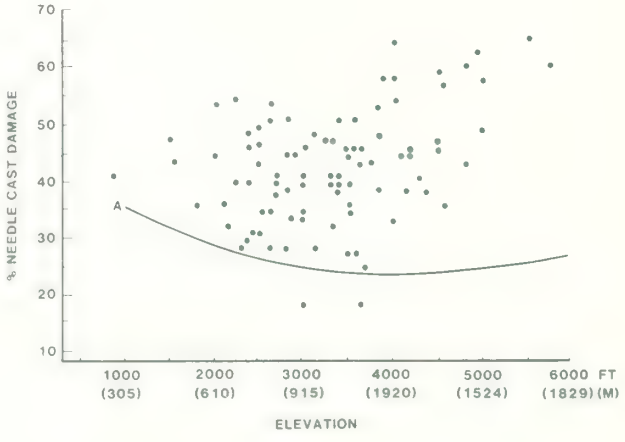


Figure 3–Actual levels of infection by *Lophodermium baculiferum* for populations of ponderosa pine plotted against elevation. The line (A) represents the predicted elevation effect (derived from the multiple regression equation) for a constant geographic effect, in this case 44 percent infection.

Table 5—Analysis of variance of infection by *Lophodermium baculiferum* on stands and families of ponderosa pine

Source of variance	df	Mean square	F value
Block	4	0.5673	
Stand	47	.2233**	3.60
Family in stand	186	.0620**	2.51
Experimental error	892	.0257	
Within plot	2,644	.0173	

**Significant at the 1 percent level of probability.

Table 6—Variance components for infection of ponderosa pine by *Lophodermium baculiferum*

Source	Variance component
Stand	0.0022
Family in stand	.0025
Experimental error	.0026
Within plot	.0173

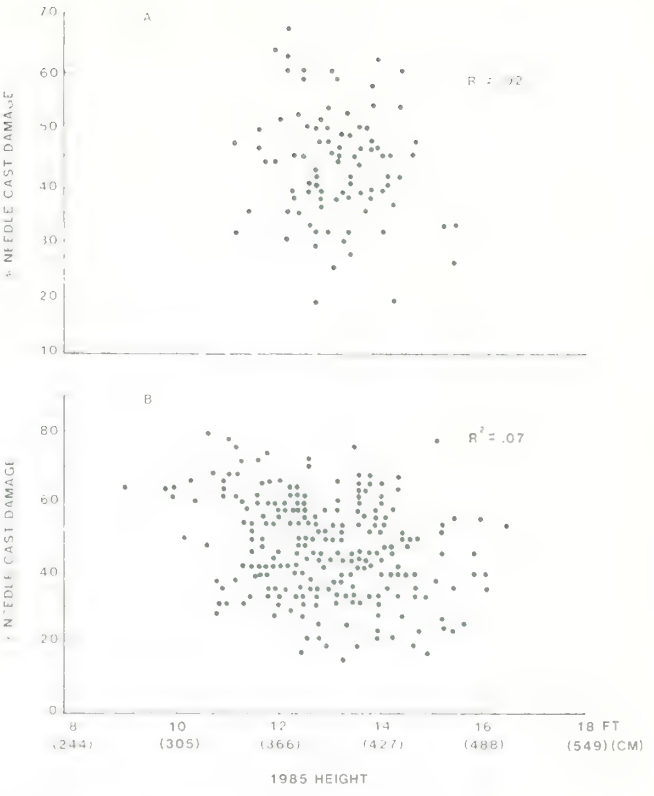


Figure 4–*Lophodermium baculiferum* infection plotted against 1985 height: A, provenance test; B, family test.

DISCUSSION

Geographic location of seed source had the most effect on the pattern of infection due to this needle cast fungus. The most resistant populations occurred in the north-central portion of the collection area. Susceptibility was most pronounced to the south. What seems to be depicted are gentle north-south clines of susceptibility to *L. baculiferum*.

We have no data concerning the level of infection for trees in the stands from which seed was collected. Consequently, there is no way of testing whether the variation pattern among stands is due to natural selection keyed to the intensity of the disease or just a chance occurrence. Nonetheless, the pattern of the damage appears to follow the climate of the Northern Rocky Mountains. The extreme northern portion of Idaho and adjacent Montana is the wettest part of the area. Usually May and June, and often July, are foggy and rainy. This general area contained the stands with the least amount of damage, that is, highest resistance. On the other hand, the stands in the extreme southern portion of the collection were from much drier areas, and their progeny had the greatest amount of damage.

Thus, it seems reasonable to conclude that resistance to this needle cast fungus is an adaptive trait that has adjusted to sites according to the amount of damage caused by needle cast.

From a practical standpoint, *L. baculiferum* seems to be only a minor problem for ponderosa pine because it shows up only when environmental conditions are favorable and only year-old or older needles are infected. Ponderosa pine in the Northern Rocky Mountains occurs in uniform pure stands only in the drier habitats where needle cast is likely to occur even less frequently than in the wetter portion of the area. Planting pure ponderosa pine plantations would probably lead to needle cast problems in these wet habitats. This supports the present prevailing forest practice of regenerating mixed stands.

The relatively high heritabilities for individuals and families indicate that substantial gains could be made in breeding for resistance to this needle cast fungus. For each unit of i (selection intensity), 14 percent gain could be made with family selection and 10 percent for individual selection. With proper seed source management, together with selection of good seed trees for natural regeneration or a fairly large inclusion of resistant trees in seed collected for artificial regeneration, additional resistance is probably not needed, especially if pure stands are not established. However, with a tree improvement program where the main purpose is to produce faster growing trees, knowledge concerning the susceptibility of the selected trees to this needle cast fungus, as well as to other diseases and insects, would be valuable to the tree breeder. It may not be necessary to increase resistance, but it is certain that resistance should not be decreased.

There appears to be only a slight relationship between relative height and the degree of damage by this needle cast fungus. In this case, the faster growing trees were the most resistant.

REFERENCES

Baumanis, I.; Pirags, D.; Spalvins, Z. 1982. Resistance trials of Scotch pine clones in the Latvian SSR. In: Resistance to disease and pests in forest trees: Proceedings of the third international workshop on the genetics of host-parasite interactions in forestry. Wageningen, The Netherlands: Center for Agricultural Publishing and Documentation: 448-449.

Harvey, G. M. 1976. Epiphytology of a needle cast fungus, *Lophodermella morbida*, in ponderosa pine plantations in western Oregon. Forest Science. 22: 223-230.

Hoff, R. J. 1985. Susceptibility of lodgepole pine to the needle cast fungus *Lophodermella concolor*. Res. Note INT-349. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 6 p.

Martinsson, O. 1979. Testing Scots pine for resistance to *Lophodermium* needle cast. Studia Forestalia Suecica. 150: 1-63.

Merrill, W.; Kistler, B. R. 1976. Seasonal development and control of *Lophodermium pinastri* in Pennsylvania. Plant Disease. 60: 652-655.

Mitchell, C. P.; Millar, C. S.; Haworth, M. N. 1976. Effect of the needle-cast fungus *Lophodermella sulcigena* on growth of Corsican pine. Forestry. 49: 153-158.

Rehfeldt, G. E. 1980. Cold acclimation in populations of *Pinus contorta* from the northern Rocky Mountains. Botanical Gazette. 141: 458-463.

Rehfeldt, G. E.; Wykoff, W. R. 1981. Periodicity of shoot elongation among populations of *Pinus contorta* from the northern Rocky Mountains. Annals of Botany. 48: 371-377.

SAS Institute, Inc. 1982. SAS user's guide: statistics. Cary, NC: SAS Institute. 494 p.

Scholz, F.; Stevens, B. R. 1982. Buffering of pH in plant organs and resistance against fungi. In: Resistance to diseases and pests in forest trees: Proceedings of the third international workshop on the genetics of host-parasite interactions in forestry. Wageningen, The Netherlands: Center for Agricultural Publishing and Documentation: 176-186.

Skilling, D. D. 1975. *Lophodermium* needle cast of pines. In: Forestry nursery diseases in the United States. Agric. Handb. 470. Washington, DC: U.S. Department of Agriculture, Forest Service: 67-68.

Skilling, D. D.; Nicholls, T. H. 1971. *Lophodermium pinastri*—a new disease problem in Scotch pine Christmas tree plantations. Plant Disease. 55: 1116-1117.

Squillace, A. E.; La Bastide, J. G. A.; Van Vredenburch, C. L. H. 1975. Genetic variation and breeding of Scots pine in the Netherlands. Forest Science. 41: 341-352.

Steel, R. G. D.; Torrie, J. H. 1960. Principles and procedures of statistics. New York: McGraw-Hill. 481 p.

Hoff, R. J. 1988. Susceptibility of ponderosa pine to the needle cast fungus *Lophodermium baculiferum*. Res. Pap. INT-386. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 6 p.

In 1985 a needle cast caused by *Lophodermium baculiferum* Mayr severely infected a provenance test and a progeny test of ponderosa pine located in northern Idaho. Populations of ponderosa pine from northern Idaho-northeastern Washington and western Montana differed in their susceptibility to needle cast. Geographic area accounted for most of the variation among populations; elevation accounted for very little. The populations in the north-central portion of the collection area were most resistant, and these were connected with the more susceptible southern populations by gentle clines. Family heritability was 0.60; for individuals it was 0.45.

KEYWORDS: disease resistance, *Pinus ponderosa*, heritability

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-387

Resistance of Ponderosa Pine to the Gouty Pitch Midge (*Cecidomyia piniinopis*)

R. J. Hoff

CLEMSON UNIVERSITY
MAY 18 1988
PUBLIC DOCUMENTS

RESEARCH SUMMARY

Individuals of a family test of ponderosa pine were scored for the amount of damage caused by infestation by gouty pitch midge. The percentage of dead or dying tips varied from 0 to 57 percent for individuals and from 0 to 20 percent for families. Heritability based on individuals was 0.48 and for families 0.60. Selection for resistance could yield a family gain of 10 percent and an individual gain of 8 percent for each unit of *i*. Use of these data in tree improvement programs is discussed.

THE AUTHOR

R. J. HOFF is principal plant geneticist with the Station's Genetics and Pest Resistance research work unit located in Moscow, ID. He received a B.A. in biology (1957) from Western Washington State University and a Ph.D. in botany (1968) from Washington State University. He has been working on the development of western white pine resistant to blister rust since 1964. He also investigates resistance to other pests in white pine and other conifers.

February 1988

Intermountain Research Station
324 25th Street
Ogden, UT 84041

Resistance of Ponderosa Pine to the Gouty Pitch Midge (*Cecidomyia piniinopis*)

R. J. Hoff

INTRODUCTION

In 1985 a heavy infestation of the gouty pitch midge (*Cecidomyia piniinopis*) was found in a plantation of ponderosa pine (*Pinus ponderosa*) in northern Idaho. The trees had been planted in rows of four trees, each row representing one family. It thus became apparent that some families were heavily damaged while others were not damaged at all.

The purpose of this paper is to document severity of infestation, and inheritance of resistance to midge attack in a ponderosa pine plantation in the Inland Northwest.

The gouty pitch midge is a native pest of forests of Eastern and Western North America. In the West, the pest is especially injurious to ponderosa pine where the level of infestation becomes high enough to kill trees (Eaton and Yuill 1960). Natural controls such as weather, host resistance, and parasites normally keep it in check (Eaton and Yuill 1960). The midge lays its eggs on rapidly growing branch and leader tips. After hatching, the larva bores through the surface until it is completely embedded in the vascular tissue. The larva feeds there until the following spring, then works to the surface to pupate. The adult emerges in 10 to 14 days. Damage occurs during larval feeding, the result of disruption of vascular tissue.

The level of midge infestation appears to be associated with the characteristics of the new shoots (Austin and others 1945). Shoots that are smooth or are covered with a waxy bloom are less infested than shoot surfaces that are sticky and resinous. Further, Duffield (1985) reported evidence that the nature of the new shoot surface was inherited and that two genes were involved.

MATERIALS AND METHODS

In 1974 the Northern Region of the Forest Service established two progeny tests of ponderosa pine in northern Idaho and one in western Montana. Other members of the Inland Empire Tree Improvement Cooperative also established tests the same year. Altogether there are six plantations. In 1985 the plantation at the Lone Mountain tree improvement site in northern Idaho exhibited high infestation by the gouty pitch midge (fig. 1).

The Lone Mountain tree improvement site is located 40 km north of Coeur d'Alene, ID. The site is flat, with only slight undulations, at an elevation of 758 m. The entire 65-ha site is surrounded by naturally regenerated ponderosa pine and lodgepole pine (*Pinus contorta*), with lesser amounts of grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*). This natural stand has an overstory of mature scattered trees (remnants of harvest) and an understory of pole-sized trees 6 to 9 m tall. Many ponderosa pine of all ages were infested with the gouty pitch midge.

Open-pollinated seed of 234 families were collected from 48 stands located in northeastern Washington and in Idaho north of the Salmon River. The number of trees per stand was usually five, sometimes four. The seedlings were grown at a Forest Service nursery near Coeur d' Alene, ID, in bare-root beds for 2 years, then lifted and planted at the Lone Mountain site in April 1974. The experimental design was a randomized complete block design with five blocks. Four progeny of each family were planted per block as a four-tree row plot.

Data were taken by estimating the number of dead or dying branch or leader tips. The range of damaged tips was determined by spending a couple of hours counting damaged tips throughout the test on several trees. From this inspection a scoring system was developed that would encompass all trees. Then the level of infestation of each tree was noted and placed in one of the following classes:

0 = 0	infested branch or leader tips, average = 0
1 = < 5	infested branch or leader tips, average = 2.5
2 = 6-32	infested branch or leader tips, average = 18
3 = 33-67	infested branch or leader tips, average = 49
4 = 68-100	infested branch or leader tips, average = 84

Tree height varied from 1.1 to 7.0 m; to determine the proportion of tips damaged on a tree basis a regression of the actual number of tips per tree (healthy and damaged) by height was determined. A random sample of 224 trees (6 percent of total trees) was selected to develop the regression formula. The data used for analysis were the percentage damage per tree, determined as follows: percent damage = number of damaged tips/TT where TT = $a + bx$, and TT = estimated total tips, x = tree height, a and b = regression coefficients, number damaged = the average associated with the field damage category. Because percentage of damage varied widely, these data were transformed (arcsin $\sqrt{\text{percent}}$) (Steel and Torrie 1960).

The analysis of variance model and expected mean squares are shown in table 1. Heritabilities followed Namkoong (1979). The relationship of gouty pitch midge damage to 1985 height was determined by regression analysis, using the GLM procedure (SAS 1979).

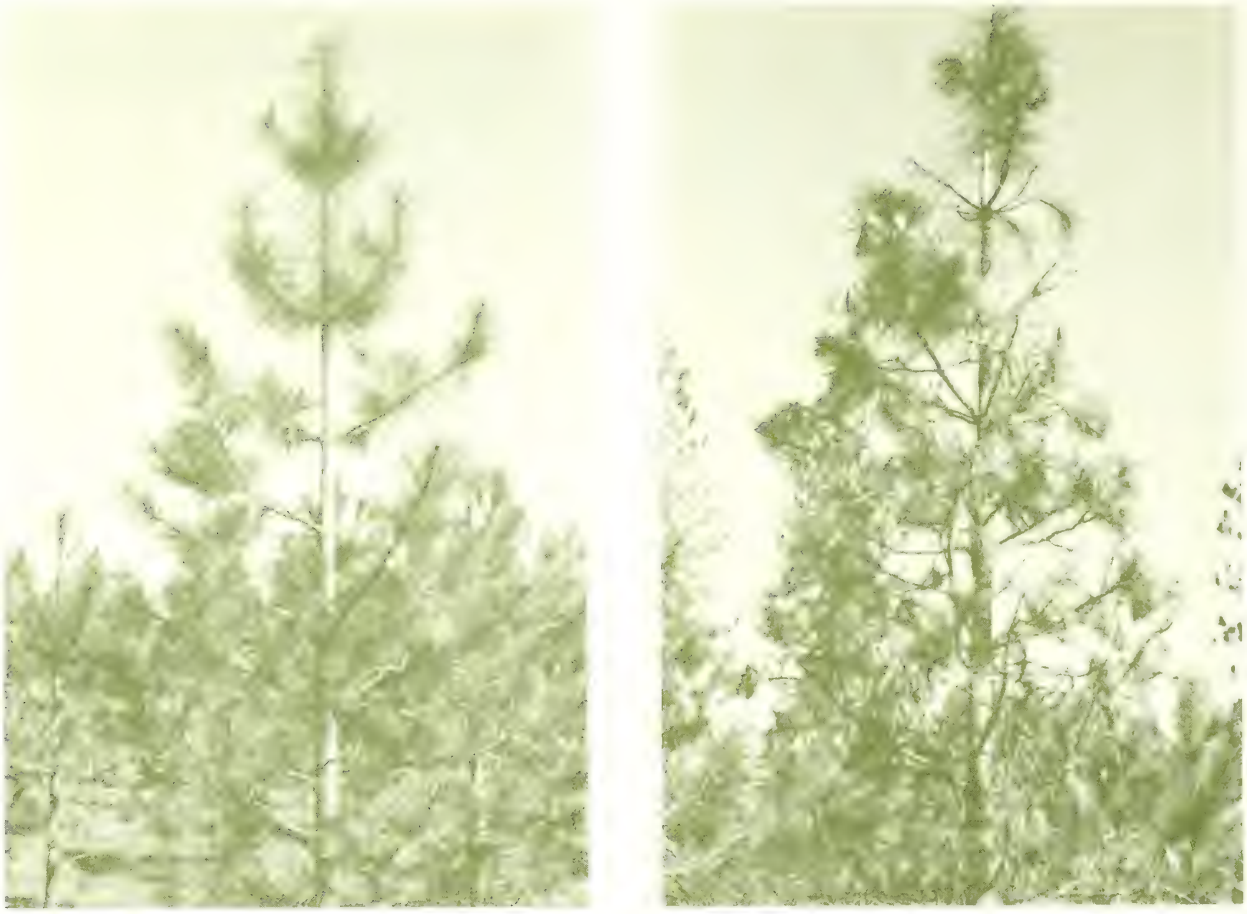


Figure 1—Gouty pitch midge damage on ponderosa pine. Tree on left was not damaged. Tree on right was heavily damaged.

Table 1—Model for analysis of variance and expected mean squares

Source of variation	df	Expected mean squares
Block	4	$\sigma^2_E + p\sigma^2_{EE} + fpST_B$
Stand	47	$\sigma^2_E + p\sigma^2_{EE} + pb\sigma^2_{FS} + pbf^*\sigma^2_S$
Family in stand	182	$\sigma^2_E + p\sigma^2_{EE} + pb\sigma^2_{FS}$
Experimental error	916	$\sigma^2_E + p\sigma^2_{EE}$
Within plot	2,608	σ^2_E

where: $b = 5$, $S = 48$, $f = 229$, $f^* = 4.6$ harmonic mean of families in stands; $p = 3.00$ harmonic mean of individuals within plots

RESULTS

The regression of total tips per tree (TT) for the sample resulted in regression coefficients of $a = -68.0$ and $b = 74.1$ tips per meter, $R^2 = 0.69$.

The average level of damage by gouty pitch midge was 5 percent. Individuals varied from 0 to 57 percent, and families varied from 0 (15 families) to 20 percent. The frequency of damage classes by individual is summarized in table 2.

Differences among families within stands were highly significant (table 3). Variance components are listed in table 3. Heritability based on individuals was 0.48; for families 0.60.

There was very little relationship between the amount of damage caused by the gouty pitch midge and the heights of the trees in 1985. R^2 for families was 0.02.

Table 2—Level of damage by gouty pitch midge on the new shoots of ponderosa pine

Infection class	Number of tips damaged		Test trees (progeny)
	Mean	Range	
			Percent
0	0	0	46
1	2.5	< 5	20
2	18	6-32	23
3	49	33-67	10
4	84	68-100	2

Table 3—Analysis of variance and variance components of transformed data

Source of variance	df	MS	Variance component
Block	4	0.367	0.0005
Stand	47	.089	.0009
Family in stand	182	.300	.0012
Experimental error	916	.012	.0017
Within plot	2,608	.007	.0070

DISCUSSION

Individuals and families of ponderosa pine vary in their response to infestation by the gouty pitch midge. The high individual and family heritabilities could result in fairly good genetic gains in resistance. The estimated gain that could be realized for one unit of i was 10 percent for family selection, 8 percent for individual selection.

Gouty pitch midge can be devastating to ponderosa pine. At the Lone Mountain tree improvement site the epidemic started in the mid-1980's. In 1986 many trees were dead, and on many others nearly all shoots were dead or dying. It will take a long time for this progeny test to recover.

Epidemics caused by the gouty pitch midge are rare in wildland forests. The biggest impact has been in test plantations, namely in a monoculture complicated by close spacing and foreign germ plasm. Nonetheless, a natural level of resistance should be maintained. It is probably not necessary to increase the level of resistance in the wildland population, unless the midge becomes a serious pest in forest plantings. The tree breeder should consider resistance in the selection scheme to make sure adequate resistance is maintained. This can be assured by carefully correlating shoot character and resistance to the midge.

REFERENCES

Austin, L.; Yuill, J. S.; Brecheen, K. G. 1945. Use of shoot characters in selecting ponderosa pines resistant to resin midge. Ecology. 26: 288-296.

Duffield, J. W. 1985. Inheritance of shoot coatings and their relation to resin midge attack on ponderosa pine. Forest Science. 31: 427-429.

Eaton, C. B.; Yuill, J. S. 1960. Gouty pitch midge. For. Pest Leafl. 46. Washington, DC: U.S. Department of Agriculture, Forest Service. 8 p.

Namkoong, G. 1979. Introduction to quantitative genetics in forestry. Tech. Bull. 1588. Washington, DC: U.S. Department of Agriculture, Forest Service.

SAS Institute. 1979. SAS user's guide: statistics. Cary, NC: SAS Institute. 494 p.

Steel, R. G. D.; Torrie, J. H. 1960. Principles and procedures of statistics. New York: McGraw-Hill. 481 p.

U S GOVERNMENT PRINTING OFFICE 1988—573-039 61,049 REGION NO 8

Hoff, R. J. 1988. Resistance of ponderosa pine to the gouty pitch midge (*Cecidomyia piniinopis*). Res. Pap. INT-387. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 3 p.

Individuals of a family test of ponderosa pine were scored for the amount of damage caused by infestation by gouty pitch midge. The percentage of dead or dying tips varied from 0 to 57 percent for individuals, and 0 to 20 percent for families. Heritability based on individuals was 0.48 and for family 0.60. The amount of gain in resistance and use of these data in tree improvement programs are discussed.

KEYWORDS: forest genetics, forest pathology, insect resistance, silviculture, reforestation

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-388

February 1988

Bracken Fern Inhibition of Conifer Regeneration in Northern Idaho

Dennis E. Ferguson
Raymond J. Boyd

CLEMSON U...
SEP 18 1988
PUBLIC DOCUMENTS

THE AUTHORS

DENNIS E. FERGUSON is a research forester, Intermountain Research Station, Forestry Sciences Laboratory, Moscow, ID. He has worked primarily with predicting regeneration establishment and growth of young trees and stands in the Northern Rocky Mountains.

RAYMOND J. BOYD is a research forester (retired), Intermountain Research Station, Forestry Sciences Laboratory, Moscow, ID. He has an extensive research background dealing with regenerating and managing young stands.

RESEARCH SUMMARY

Results of investigations on allelopathy of bracken fern in northern Idaho are reported. The study objective was to gain an understanding of how bracken fern interferes with establishment of conifers and shrubs, often to their complete exclusion.

Containerized conifer seedlings grown in pots of soil from a bracken fern glade grew less than seedlings grown in pots of forest soil or potting mix. Mortality was minimal. In greenhouse tests, bracken soil had little effect on germination of conifer and shrub seeds. Although statistically significant differences were found in germination and growth of shrub species, the differences are not significant in a practical sense because sufficient seed of all species became established and grew in greenhouse conditions. Five soil depths were also tested to determine the depth to which phytotoxins might be effective in preventing seedling establishment. Only the 0- to 5-cm layer of bracken soil decreased germination and growth of shrub species.

Additional testing was conducted under field conditions. Conifer seed was stratified over the winter on soils in bracken glades and on potting mix transported to the site. In the spring, seeds germinated well on both soil types, but most seeds germinating on bracken soil died. Radicles were long, indicating adequate germination energy, but germinates died before shedding seedcoats. Radicles were dark brown to black in color. Seeds that germinated on potting mix were healthy and shed their seedcoats, but some radicle tips were slightly discolored.

Death of germinants in this study probably resulted from absorption of bracken phytotoxins that have accumulated in the soil over a number of years. Phytotoxins are thought to be concentrated in a thin layer near the soil surface. Allelopathy tests should be conducted under field conditions because transporting, mixing, or drying the soil can reduce the effect of phytotoxins bound in the soil complex.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Bracken Fern Inhibition of Conifer Regeneration in Northern Idaho

Dennis E. Ferguson
Raymond J. Boyd

INTRODUCTION

Bracken fern (*Pteridium aquilinum* [L.] Kuhn) is the most widely distributed vascular plant in the world (Page 1982), and Taylor (1985) calls bracken the most successful international weed of the 20th century. It is a highly competitive species in grazing areas and disturbed woodlands. Invasion can be through spore germination or expansion of rhizomes. Bracken's success has been attributed to its ability to compete for moisture, nutrients, and light, smothering of other plants by senescing fronds, unpalatability of bracken to animals and insects, lack of disease problems, a rhizome system that readily sprouts following disturbance, and chemical interference with other plants (allelopathy).

In northern Idaho, bracken fern can be a vigorous competitor in forests and pastures. Bracken also occupies ⅕- to 6-ha glades where woody vegetation is virtually excluded and only a few forb and grass species grow. The absence of woody species and charcoal fragments in glade soils suggests bracken has been dominant for perhaps hundreds of years.

Phytotoxins released by bracken fern can inhibit the establishment and growth of associated species. The allelopathic effect of bracken has been reported in other parts of the world and could be a factor operating in bracken-dominated areas of northern Idaho. We conducted investigations to test the allelopathic potential of bracken fern in northern Idaho and gain an understanding of the mechanism(s) causing regeneration failures.

LITERATURE REVIEW

Bracken fern is a widely distributed weed species, causing problems in places such as Africa, India, Australia, New Zealand, North America, South America, and the British Isles (Cody and Crompton 1975; Gliessman 1976). Published information on bracken is quite extensive, and excellent review articles are available (Braid 1959; Cody and Crompton 1975). Increases in abundance of bracken are correlated with clearing of farm and forest by man (Page 1982; Rymer 1976). Bracken has a cumulative toxic effect on livestock (Cody and Crompton 1975; Cooper-Driver 1976) and is linked to cancer in humans (Evans 1976; Hirono 1981; Hirono and others 1972). In addition, studies have shown bracken produces phytotoxins that interfere with establishment and growth of other plants.

Bracken fern is usually a minor component of native forests but increases with disturbance by fire, harvesting, or grazing. Windblown spores disperse bracken over long distances, although the main reproductive method is expansion of underground rhizomes. Spores evidently need nearly sterile soil conditions before germination will occur (Cody and Crompton 1975; Page 1982). Cody and Crompton (1975) note that there are no published reports of spores germinating under natural conditions in Canada. Sporelings have been observed in Britain and elsewhere, but not in abundance.

Bracken fern's extensive rhizome system spreads rapidly. Conway (1952) grew a young plant in a trough to document vegetative reproduction. Forty-five fronds were produced the second growing season, 136 the third, and 297 the fourth season. Znerold (1979) calculated frond density of 286,300 stems/ha at a bracken glade in northern Idaho.

About one-fifth of the underground buds produce fronds in the spring. Dormant buds provide a reservoir of potential fronds to replace those killed by frost, fire, or other agents. The deep rhizome system is impervious to most damaging agents and readily resprouts.

Disturbances favor bracken fern over associated species. Bracken is difficult to control and nearly impossible to eradicate. The best long-term control is by repeated cuttings, cultivation, or herbicides (Martin 1976; Preest 1975). Herbicides are probably the most effective method of control because the rhizomes are killed.

Livestock have been used to control bracken, but they do not prefer bracken as a food source. Bracken is toxic to livestock if eaten for several weeks or months. Poisoning, which has been frequently documented, affects cattle, horses, and sheep differently (Hirono 1981). Pamukcu and others (1978) have shown that the milk of cows fed bracken fern has toxic, carcinogenic, and mutagenic properties.

Bracken fern also gains a competitive advantage over other plants through chemical interference. Allelopathic compounds in many plants, including bracken, are thought to be metabolic byproducts that have accumulated in the plant and are often stored in localized plant parts such as vacuoles and cell walls (DeBell 1970; Fisher 1979; Whittaker and Feeny 1971). Leaching and decomposition release phytotoxins into the environment. Microbial action breaks chemicals down into secondary plant chemicals, which are also potential phytotoxins.

Rice (1979, 1984) reviews the subject of allelopathy and discusses bracken and other ferns. The remainder of this review discusses the allelopathic potential of bracken.

Gliessman and Muller (1972) demonstrated that water leachate from bracken fronds reduces radicle growth of

brome grass (*Bromus rigidus*). Dead fronds collected before fall rains were the most toxic. Average 48-hour radicle length of seed soaked 2 hours in bracken leachate was 82.2 percent of the control groups. Quadrupling the leachate concentration decreased radicle elongation to 31.4 percent of the control. Leachate from green fronds was not toxic; yellowing fronds were toxic only at concentrated levels. Leachate did not reduce germination of the brome grass, but wild oat (*Avena fatua*) germination was reduced to 76 percent of the control.

Gliessman and Muller (1978) also reported on experiments excluding other factors thought to be responsible for bracken's dominance. Eliminated were animals, soil differences, and competition for light, moisture, and nutrients. These factors account for some differences between bracken-dominated land and adjacent grasslands but were not the major reasons for the differences. They conclude that allelopathy, in the form of water-soluble phytotoxins from dead fronds, is the primary mechanism accounting for bracken dominance.

A few studies have reported on allelopathic effects of bracken on conifers. Stewart (1975) found that extracts from senescent bracken fronds did not reduce germination of Douglas-fir (*Pseudotsuga menziesii*) but did reduce germination of western thimbleberry (*Rubus parviflorus*) and delayed germination of salmonberry (*Rubus spectabilis*). In Stewart's study, seeds moistened with either distilled water or bracken leachate were stratified in vermiculite and germinated on sterile pumice.

In a corresponding greenhouse experiment, Stewart germinated seeds on untreated forest soil, on forest soil with seeds covered by bracken frond material, and on forest soil in which bracken frond material was mixed with the soil. When seeds were covered by bracken, germination of Douglas-fir was 58 percent versus 65 percent for untreated soil. Germination of salmonberry and thimbleberry was also reduced in pots having seeds covered by bracken (2 percent germination for salmonberry versus 14 percent in the control and 29 percent germination for thimbleberry versus 65 percent in the control). Shoot length and dry weight of thimbleberry seedlings were reduced in pots where bracken was mixed with the soil.

Del Moral and Cates (1971) showed that water extracts from bracken fern reduced growth of Douglas-fir, but the effect was barely significant. Results are not conclusive in this instance because green frond material was used, which Gliessman and Muller (1972) later found to be nontoxic.

Seedlings have been successfully planted in cutover forests dominated by bracken fern. Dimock (1964) reported 79 percent survival of Douglas-fir seedlings planted on a productive site in western Washington. But growth was extremely slow, with trees averaging only 29.5 cm tall after four growing seasons. A planting study by Boyd and Znerold (in preparation) was confounded by high losses of planted trees to pocket gophers (*Thomomys* sp.). Survival after 7 years was only 15 percent, leaving 463 trees available for height measurement. Heights of trees planted in plots where bracken had been eliminated were nearly twice the heights of trees growing in bracken-dominated plots.

Allelopathic effects can also be indirect. Chemicals released by plants could stimulate harmful microorganisms or suppress helpful ones (Rice 1979). The relationship between bracken fern and beneficial mycorrhizal fungi has been explored. Acsai and Largent (1983) found no effect of bracken phytotoxins on ectomycorrhizae formation with white fir (*Abies concolor*) or Douglas-fir in northern California. Rose and others (1983) found mixed effects during in vitro studies on growth of four mycorrhizal fungi. One fungus was stimulated, two were inhibited, and the other was not affected.

Buildup of phytotoxins in the soil depends on the amount produced, the rate at which the compounds are deactivated, and soil characteristics (Rice 1979). Phytotoxic effects seem most pronounced in soils that are heavy in texture, poorly aerated, moist a good portion of the year, and often cool in temperature (DeBell 1970; Fisher 1978; Horsley 1977; Rietveld and others 1983). For example, Rietveld and others felt that juglone from black walnut (*Juglans nigra*) was not harmful until the walnut trees were large enough to produce substantial amounts which, in combination with wet soils that reduced microbial activity, allowed juglone to accumulate in the soil.

Phenolic acids have been identified as the most probable cause of bracken's allelopathic effect. Phenolic acids are water soluble and thus able to leach from fronds into the soil. Cinnamic and benzoic acids are the two most frequently mentioned phenolic acids associated with bracken. Derivatives of cinnamic acid include *p*-coumaric acid, caffeic acid, and ferulic acid while derivatives of benzoic acid include *p*-hydroxybenzoic acid, vanillic acid, and protocatechuic acid (Bohm and Tryon 1967; Glass and Bohm 1969; Whitehead 1964).

Many studies show a statistically significant reduction in germination or growth attributable to bracken fern allelopathy, but the magnitude of these results does not demonstrate how woody species could be virtually eliminated from bracken glades in northern Idaho. When one considers seedfall from species adjacent to bracken glades, even a low percentage germination should result in higher coverage of these species over time.

Some light has been shed on the reason for differences between field observations and results of greenhouse and laboratory tests. Moving, drying, or mixing the soil may result in detoxification of plant residues. Microbial activity might be altered by changes in the temperature or moisture regime of the soil; and if the soil is mixed, allelopathic chemicals might be diluted. Brown (1967) suggests that soil compounds quickly break down once the soil is removed from the field site to the greenhouse. Fisher (1978) found that soil containing juglone was detoxified if allowed to dry before bioassay tests were started, whereas the inhibitory effects remained strong when the soil was not dried.

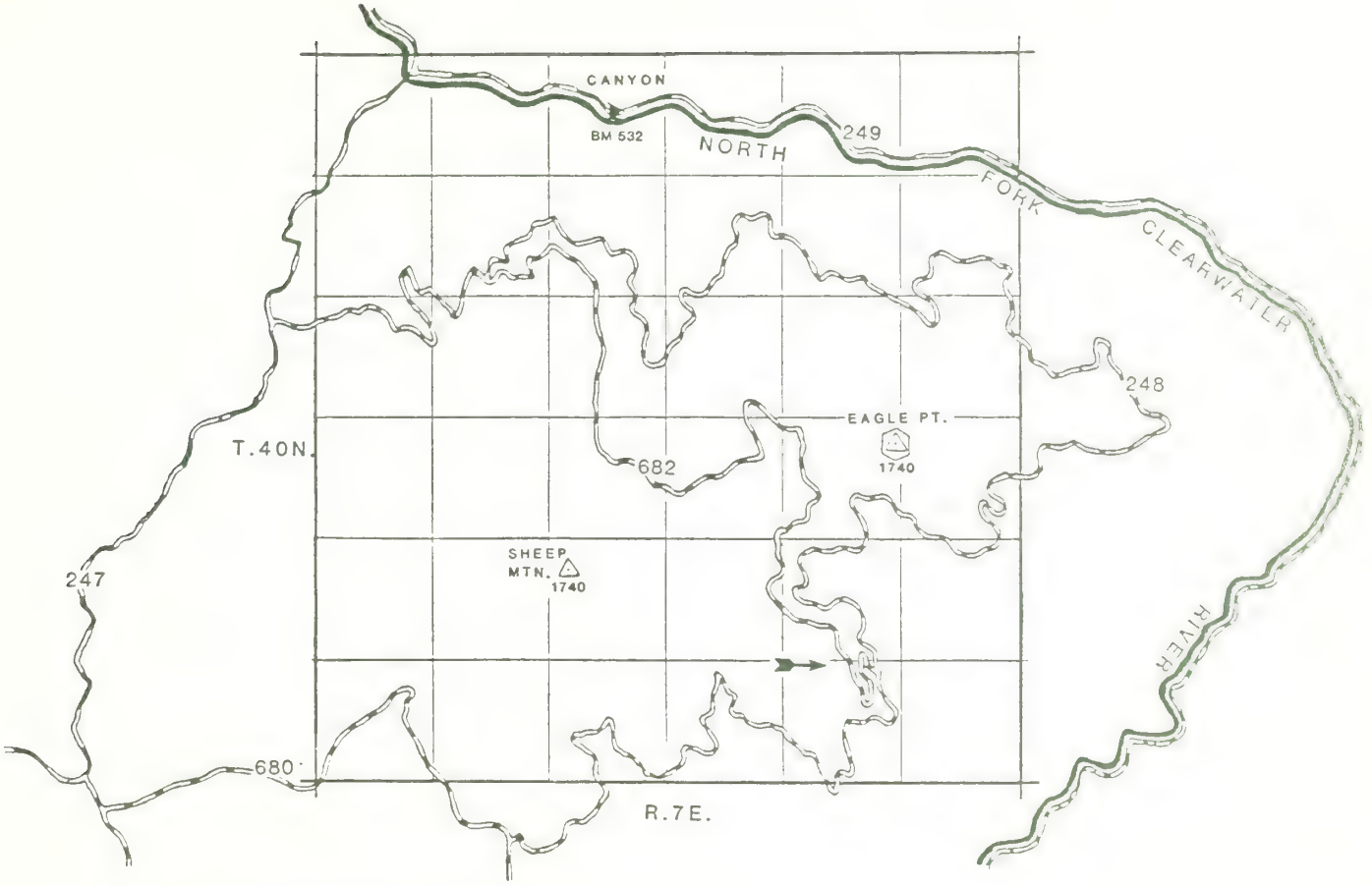


Figure 1—Eagle Point study area (arrow) on the North Fork Ranger District.

EAGLE POINT STUDY SITE

Research was conducted in and near bracken glades south of Eagle Point on the North Fork Ranger District of the Clearwater National Forest (figs. 1 and 2). Elevation of the site averages 1,430 m above sea level. Aspect is easterly, with slope angles of 20 to 50 percent. The most prevalent habitat type is *Abies grandis/Asarum caudatum* (grand fir/wild ginger) as described by Cooper and others (1987).

Soils are dark brown to black silt loams (Wilson and others 1983). The dark-colored umbric soil surface layer is loessal material influenced by ash from Mount Mazama (Crater Lake). Also characteristic of the area is a high organic turnover rate in the soil (similar to prairie grasslands), deep snowpacks during the winter, and areas with high water tables, at least during a portion of the year.

Several bracken glades existed prior to harvesting adjacent forests (fig. 3). Within the glades, there is scant evidence of past or present woody vegetation; neither buried wood nor charcoal fragments are found. Herbaceous species other than bracken include glacier-lily (*Erythronium grandiflorum*), larkspur (*Delphinium* sp.), starwort (*Stellaria obtusa*), coneflower (*Rudbeckia occidentalis*), and occasional wild ginger, sedges (*Carex* sp.), and grasses.

In the harvested areas, coverage by bracken fern has expanded, and these areas now contain a mixture of bracken, shrubs, forbs, grasses, and some conifer regeneration. The study site has been planted several times without success, not only because of bracken fern but also high populations of pocket gophers and big game use. Natural regeneration has become established mainly along skid trails and roads.

Portions of the study site were treated in 1977 with the herbicide asulam to test control effectiveness and performance of planted conifers (Boyd and Znerold in preparation; Znerold 1979). Bracken control was excellent, but pocket gopher and big game damage confounded the planting trials. The sprayed areas now support more grasses, sedges, and forbs than unsprayed controls, but bracken is reinvading and frond density is nearly the same as before spraying. Sprayed areas are used as one treatment in this study.

Figure 2—View of cutover area showing intermixing of bracken, stumps, and brush.

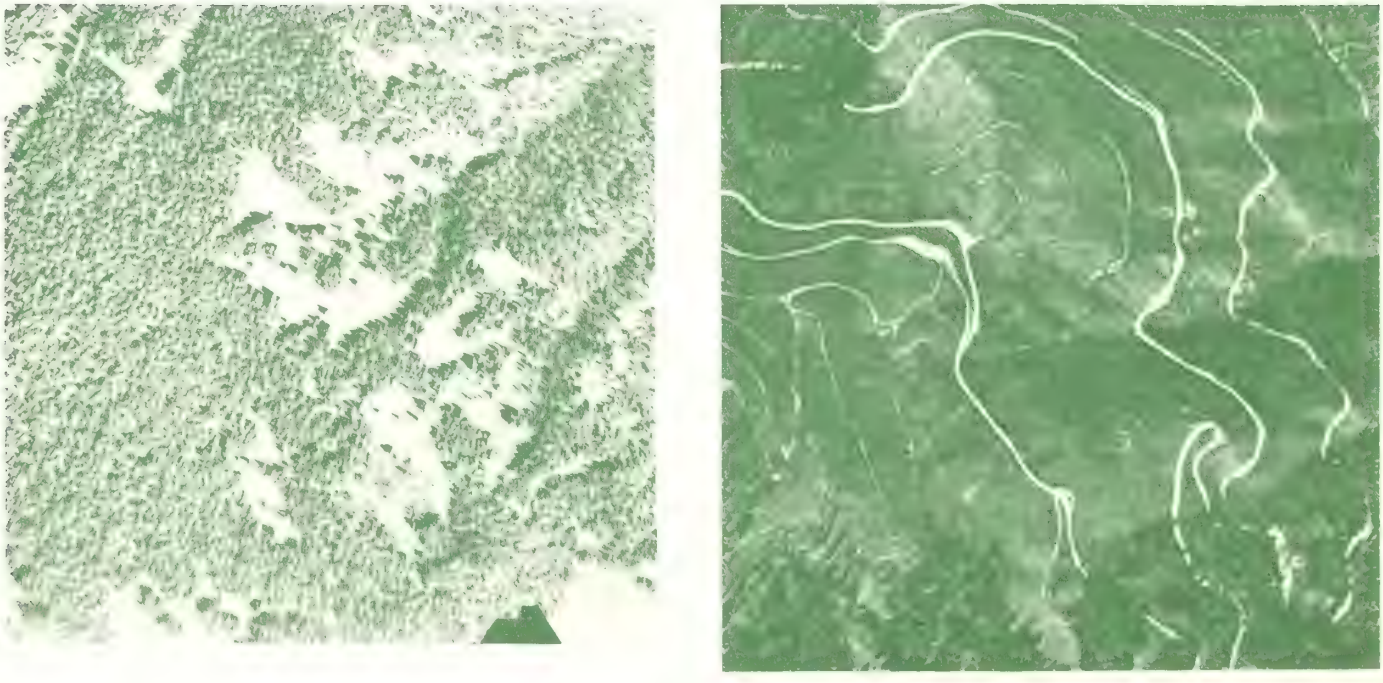


Figure 3— Aerial view of Eagle Point study site in 1956 (left) and 1981 (right).

PLANTING STUDY

Procedures

In the spring of 1984, soil was collected at Eagle Point and placed in 1.9-liter pots. The four treatments were bracken glade, bracken glade sprayed in 1977 (Znerold 1979), adjacent forest, and forestry potting mix (1:1 ratio of peat and vermiculite). Five replications were sampled in each treatment, with 10 soil samples taken from each replicate, for a total of 200 pots. The soil was lifted intact by pushing a hollow metal cylinder into the ground, clamping onto the sample, lifting it out, and placing it into the pot.

Pots were randomly arranged by replication in a shadehouse (50 percent reduction in light) in Moscow, ID. Two container-grown seedlings were planted in each pot—one Douglas-fir and one grand fir in the first 100 pots, and two Engelmann spruce (*Picea engelmannii*) in each of the other 100 pots. Plastic fruit container lids were sealed, inverted, and placed under individual pots to provide a reservoir of water, reduce leaching, and prevent transfer of leachates among pots.

Seedlings were grown for two summers. Fresh bracken fern litter was not added between growing seasons. At the end of the second summer, seedlings were measured for second-year height growth and total green top weight.

Results

Few seedlings died—four grand fir and two spruce. But tops or branches sometimes died in the bracken treatments. Eighteen trees had tops or branches that were dead; of these, 14 trees were from one of the bracken fern treatment soils.

Height growth during the second year and total green top weight were chosen to test treatment differences. Growth the year of planting is largely a function of predetermined buds while growth the second year reflects conditions experienced by the seedlings since planting. Total green top weight was recorded as an expression of biomass production.

Results of analysis of variance are shown in table 1. The number of trees in each analysis is reduced by the number of dead trees and, in the case of growth, the number of trees with dead tops. Patterns are similar for all three species. Trees in forest and potting mix soils consistently outperform either of the bracken treatments. Trees in the forest soil or potting mix have about 1.8 times the height increment and 1.6 times the top weight of those in the bracken soil treatments. Growth and top weight are consistently lower in the sprayed bracken compared to the unsprayed, but this difference is not significant in most of the comparisons.

Treatment differences may be conservative in that litter was not added between the two growing seasons and the soil plug around the roots of container-grown seedlings provided a reserve of soil not influenced by bracken fern. Long-term effects on mortality are unknown because, in natural conditions, conifer roots may contact bracken rhizomes or residues from decomposing fronds.

BIOASSAY STUDY

Procedures

This study was conducted in conjunction with the planting study just described. The objective was to determine if bracken soil reduced germination and growth of woody species and, if so, how far into the soil might the phytotoxins be effective.

Three native soil treatments were used: bracken glade, sprayed bracken glade, and adjacent forest. Five soil pits per treatment were dug to a depth of 60 cm or to soil parent material, whichever was deeper. Six soil samples were collected from each pit at levels of 0 to 5 cm, 13 to 18 cm, 28 to 33 cm, 43 to 48 cm, 60 to 90 cm, and a mixture of the five levels. Soil was transported in plastic bags to the Moscow laboratory.

Seeds of eight species were sown in this test: Douglas-fir, grand fir, Engelmann spruce, subalpine fir (*Abies lasiocarpa*), Rocky Mountain maple (*Acer glabrum*), huckleberry (*Vaccinium globulare*), Sitka alder (*Alnus sinuata*), and chokecherry (*Prunus virginiana*). Seeds were sown in 1-liter pots, with 2 species per pot, 25 seeds per species. Thus, the study design is 3 treatments × 5 replications × 6 depths × 8 species × 25 seeds per species, for a total of 18,000 seeds. Conifer seed was not stratified, but shrub seed had been stratified by a local nursery specializing in growing native plants.

Table 1—Planting study: containerized seedling mean 1985 height increment (growth) and total green top weight (top weight) by treatment and species. Within column, means followed by different letters are significantly different at the 5 percent level, using Duncan's multiple range test

Treatment	Douglas-fir		Grand fir		Spruce	
	Growth	Top weight	Growth	Top weight	Growth	Top weight
	mm	*g*	*mm*	*g*	*mm*	*g*
Bracken	35.4[b]	117.3[c]	32.2[b,c]	109.8[b]	19.3[b]	25.3[b]
Sprayed	31.4[b]	91.0[c]	19.9[c]	78.1[c]	16.9[b]	24.1[b]
Forested	57.3[a]	155.6[b]	49.9[a]	129.9[b]	32.6[a]	38.5[a]
Potting mix	68.3[a]	266.4[a]	38.9[a,b]	160.1[a]	29.1[a]	32.3[a]
No. of trees	92	100	93	96	198	198

Table 2—Bioassay study: percentage germination and results of analysis of variance by species, treatment, and soil depth. Each figure is the average of five replicates of 25 seeds. Within species and column, means followed by different letters are significantly different at the 5 percent level, using Duncan's multiple range test

Species	Treatment	Soil depth, cm					
		0-5	13-18	28-33	43-48	60-90	Mixed
		Germination percent					
Huckleberry	Bracken	17.6[a,b]	28.0[a]	45.6[a]	52.0[a]	61.6[a]	32.8[a,b]
	Sprayed	9.6[b]	26.4[a]	53.6[a]	54.4[a]	55.2[a]	9.6[b]
	Forested	28.0[a]	31.2[a]	35.2[a]	57.6[a]	60.0[a]	41.6[a]
Alder	Bracken	26.4[b]	41.6[a]	59.2[a]	50.4[a]	60.0[a]	57.6[a]
	Sprayed	28.8[a,b]	49.6[a]	62.4[a]	61.6[a]	58.4[a]	54.4[a]
	Forested	45.6[a]	48.8[a]	60.0[a]	61.6[a]	55.2[a]	56.0[a]
Subalpine fir	Bracken	53.6[a]	59.2[a]	56.8[b]	69.6[a]	20.0[b]	36.0[b]
	Sprayed	53.6[a]	56.0[a]	73.6[a]	60.8[a]	41.6[a]	61.6[a]
	Forested	47.2[a]	53.6[a]	50.4[b]	42.4[b]	18.4[b]	57.6[a]
Engelmann spruce	Bracken	48.0[a]	57.6[a]	59.2[a]	59.2[a]	54.4[a]	48.8[a]
	Sprayed	57.6[a]	55.2[a]	64.0[a]	61.6[a]	58.4[a]	50.4[a]
	Forested	54.4[a]	59.2[a]	62.4[a]	56.0[a]	60.8[a]	51.2[a]
Douglas-fir	Bracken	43.2[a]	61.6[a]	57.6[a]	71.2[a]	43.0[a]	55.2[a]
	Sprayed	35.2[a]	55.2[a]	52.0[a]	49.6[b]	43.2[a]	49.6[a]
	Forested	25.6[a]	53.6[a]	36.8[a]	52.8[b]	31.2[a]	58.4[a]
Grand fir	Bracken	69.6[a]	82.4[a]	84.0[a]	82.4[a]	77.0[a]	72.8[a]
	Sprayed	72.8[a]	80.8[a]	82.4[a]	76.8[a]	75.2[a]	81.6[a]
	Forested	68.8[a]	80.8[a]	75.2[a]	77.6[a]	78.4[a]	80.0[a]

Seed was sown in late June through early July 1984, covered lightly with grit, and placed in a greenhouse. Watering was from below, using inverted fruit container lids under each pot, and from above using a fine mist to keep seeds moist.

Germination was recorded at regular intervals throughout the summer. Grand fir and Douglas-fir germinated quickly and were thinned to the tallest three trees after germination was essentially complete.

Results

Two of the eight species, maple and cherry, did not germinate in sufficient numbers to include in the analysis. The seed appeared healthy; most likely the stratification requirements had not been met. Germination of huckleberry and alder was significantly reduced (5 percent significance level) in the 0- to 5-cm soil depth for both bracken treatments (table 2). Germination of huckleberry was also reduced in the mixed soil. Conifer seed germination was good, and comparisons of treatment means show few significant differences. Certainly, sufficient seed germinated in each treatment to successfully establish these species.

Seedling heights at the end of the first growing season were compared (table 3). For each group of 25 seeds, the tallest three germinants were recorded and averaged. Sometimes only one or two germinants were available. The average height per pot by species was used in an analysis of variance.

There is a trend for huckleberry and alder to be taller in the forest soil treatment for all soil depths. This trend is statistically significant at the 5 percent level in the 0- to 5-cm soil depth and the mixed soil. Here, huckleberry and alder in the forest treatment soil are roughly twice as tall as in bracken treatment soil.

Within soil depth, conifers show little difference among treatments. Conifer heights decrease with increasing soil depth, but this trend is not related to treatment.

SEED STRATIFICATION STUDY

Procedures

The planting and greenhouse bioassay tests show that woody species can germinate and grow in soil previously dominated by bracken fern. Further testing needed to be done in natural environments. The next step was to stratify seed at the Eagle Point study site.

Seeds of Douglas-fir, grand fir, Engelmann spruce, and subalpine fir were sown on three native soils and on potting mix transported to the study area. The soils selected were bracken glade, sprayed bracken glade, and adjacent forest. The forest site has a closed canopy overstory in contrast to the open conditions in the bracken sites. The 4 species × 3 treatments × 2 soil types were replicated 6 times, 25 seeds per replicate, for a total of 3,600 seeds.

The potting mix was placed in 10-cm deep aluminum pans. The pans were buried in treatment areas, with the surface of the potting mix level with the soil surface and

Table 3—Bioassay study: analysis of variance on first-year average height (mm) of the three tallest seedlings for each species, treatment, and soil depth. Each figure is the average of five replicates. Each replicate is represented by the average height of the three tallest seedlings if available; otherwise two or one seedling. Within species and column, means followed by different letters are significantly different at the 5 percent level using Duncan's multiple range test

Species	Treatment	Soil depth, cm					
		0-5	13-18	28-33	43-48	60-90	Mixed
		Average height, mm					
Huckleberry	Bracken	3.0[b]	3.4[a]	4.9[a]	3.9[a]	3.1[a]	3.3[a,b]
	Sprayed	2.3[b]	2.5[a]	4.5[a]	3.6[a]	3.2[a]	2.5[b]
	Forested	6.4[a]	4.3[a]	4.6[a]	4.1[a]	4.3[a]	7.1[a]
Alder	Bracken	11.5[b]	12.7[a,b]	9.2[a]	6.5[b]	6.8[a]	7.6[b]
	Sprayed	10.5[b]	6.7[b]	8.0[a]	4.5[b]	6.1[a]	6.8[b]
	Forested	23.8[a]	18.3[a]	13.8[a]	11.1[a]	8.2[a]	15.4[a]
Subalpine fir	Bracken	14.9[a]	15.1[a]	13.7[a]	13.5[a]	11.1[a]	12.9[a]
	Sprayed	15.6[a]	13.9[a]	15.5[a]	14.3[a]	13.9[a]	15.3[a]
	Forested	15.7[a]	13.7[a]	13.5[a]	12.9[a]	11.6[a]	13.7[a]
Engelmann spruce	Bracken	13.9[b]	14.0[a]	13.3[a]	12.7[a]	11.2[a]	12.9[a]
	Sprayed	15.4[a,b]	14.8[a]	13.0[a]	13.3[a]	11.2[a]	14.2[a]
	Forested	17.5[a]	14.1[a]	12.6[a]	11.3[b]	11.5[a]	13.5[a]
Douglas-fir	Bracken	31.5[a]	31.4[a]	28.8[a]	27.5[a]	21.9[b]	30.2[a]
	Sprayed	30.1[a]	32.0[a]	31.9[a]	27.4[a]	25.0[a,b]	32.4[a]
	Forested	33.8[a]	29.1[a]	28.5[a]	27.7[a]	28.5[a]	30.1[a]
Grand fir	Bracken	27.7[a]	29.6[a]	26.3[a]	26.3[a]	24.9[a]	28.3[a]
	Sprayed	29.1[a]	27.3[a]	27.8[a]	28.3[a]	26.2[a]	29.6[a]
	Forested	27.7[a]	30.0[a]	29.6[a]	29.9[a]	27.9[a]	30.7[a]

the side of the pan extending about 2 cm above ground level. A hole on the bottom, downhill side of each pan provided drainage. The purpose of the potting mix was to separate the effects of the current year's litter from the effects of the native soil.

Nylon mesh seed packets were prepared to enable recovery of seed after stratification. Packets were 15 cm^2 and sewn into quarters to hold 25 seeds of each species. Packets were labeled, enclosed with wire screening to prevent rodent feeding, and placed at the study site on October 4 and 5, 1984. In October, the bracken fronds were brown but standing, and the wet season had not begun.

Six replications of seed packets were placed in each treatment area. Packets placed on native treatment soil were tethered by a wire to a stake driven into the ground. Loose litter was brushed away to ensure seed packets were in contact with the soil surface. Small wires pinned seed packets to the ground.

Six replications of seed packets in potting mix soil were placed in an aluminum pan. Litter removed when burying the pans was replaced on top of the packets. Then standing fronds in bracken treatments were bent over the pans and covered with hardware cloth to hold the litter and seed packets in place.

Seed was overwintered at the site and collected on June 5, 1985. Although the study site was free of snow before June 5, earlier access was prevented by snowdrifts in the roads. Soil and seed packets were transported to Moscow and stored in a cooler at 2 °C while seeds were examined and transferred to germination trays.

As an additional check on seed viability, six replications of seed for the four conifer species were placed in germination trays. Seed was stratified for 10 minutes in a solution containing 60 percent distilled water and 40 percent bleach (the bleach contained 5.25 percent sodium hypochlorite), then rinsed for 65 hours in running water—a procedure recommended by Advincula and others (1983). Each germination tray held 25 seeds of one species, the seeds being placed on filter paper and moistened with distilled water. These trays, and those containing seed stratified at the study site, were kept in growth chambers at 30 °C and 8 hours of light alternated with 20 °C and 16 hours of darkness.

Results

Much of the conifer seed germinated at the study site, and radicles had penetrated the nylon mesh and wire screen. Ungerminated seed was transferred to germination trays, but few of these seeds germinated. Molds eventually became a problem, and moldy seed was discarded to prevent contamination of other seed.

Results of seed germination are summarized in table 4. First, total percentage of germination is shown by species, treatment, and soil type. This figure includes all seed that germinated (radicle length $\geq$ seed length). Next is shown the percentage of seed that had germinated but was dead

Table 4—Seed stratification study: Percentage germination of conifer seed on treatment soil and potting mix by species, treatment, and status. Each figure is the average of six replications of 25 seeds. Within species, treatment, and status, means followed by different letters are significantly different at the 5 percent level using Duncan's multiple range test. For total percent germination, underlining indicates no significant difference between this mean and the mean for the stratified control in the right-hand column

		Treatment and soil type						
		Bracken glade		Sprayed bracken		Forested		
Species	Status[1]	Soil	Mix	Soil	Mix	Soil	Mix	Stratified control
Subalpine fir	Total germinated	77.3[a]	80.6[a]	64.0[a]	86.8[a]	8.7[b]	47.7[a]	62.7
	Germinated and dead	73.3[a]	1.3[b]	64.0[a]	15.4[b]	2.0[a]	1.5[a]	
Engelmann spruce	Total germinated	14.0[a]	16.8[a]	2.0[a]	4.0[a]	0.0[a]	10.0[a]	32.9
	Germinated and dead	0.0[a]	0.7[a]	0.7[a]	0.0[a]	0.0[a]	1.3[a]	
Douglas-fir	Total germinated	46.0[b]	86.3[a]	38.7[b]	76.6[a]	4.0[b]	25.6[a]	78.7
	Germinated and dead	35.3[a]	0.0[b]	28.7[a]	0.0[b]	0.7[a]	0.7[a]	
Grand fir	Total germinated	66.7[a]	71.3[a]	71.3[a]	81.1[a]	5.3[b]	54.3[a]	38.7
	Germinated and dead	66.0[a]	20.2[b]	71.3[a]	33.6[b]	1.3[a]	8.9[a]	

[1]Total germinated: average total germination regardless of whether seedlings lived or died. Germinated and dead: average percentage of seeds that were dead when seed packets were opened.

when seed packets were opened. This percentage is for the number of seeds sown, not just those that germinated.

The most noticeable difference in table 4 is the percentage of dead seedlings on the bracken fern soils compared to potting mix soil. Most seed germinating on bracken soil were dead when the seed packets were opened, whereas most seed germinating on potting mix were alive. Germinants on both soil types had radicles up to 3 cm long, displaying considerable germination energy, but seed on native bracken soils died before shedding their seedcoats. Radicles in bracken soils were shriveled and dark brown (fig. 4). Germinants in potting mix treatments shed their seedcoats and radicles extended into the potting mix (fig. 5), although some radicle tips were brown.

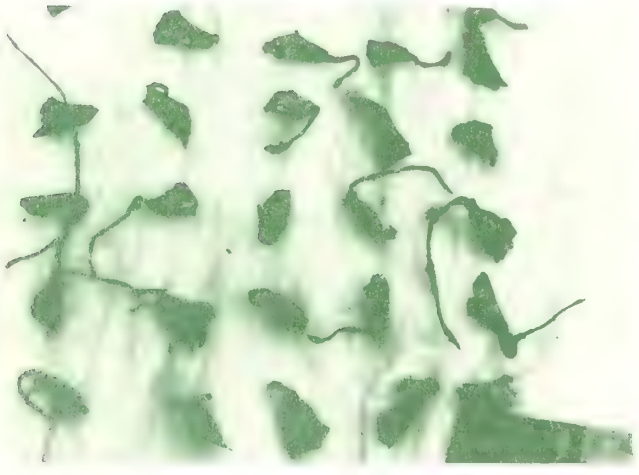


Figure 4—Seed from a seed packet stratified on bracken soil. Seed died after radicle elongation but before shedding seedcoats.

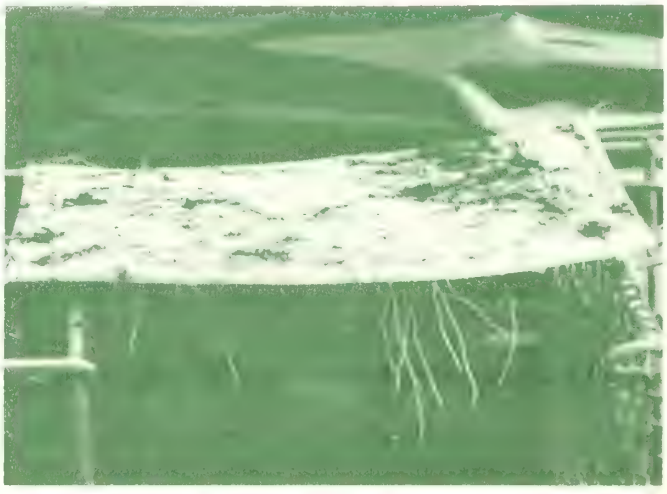


Figure 5—Seed packet from the potting soil portion of the seed stratification study. Note the healthy radicles that have penetrated the mesh seed packet.

Table 4 also shows that in the native bracken soils, total percentage of germination is not significantly different than germination on potting mix, with the exception of Douglas-fir. When total germination between the two soil types is the same, differences in percentage of seed germinating but dying can be attributed to soil type. Said another way, stratification of seed in bracken environments did not reduce germination, but major differences in survival developed after seed germination. Douglas-fir germination seems to have been affected by stratification because seed overwintered on bracken soil has significantly lower total percentage germination than on potting mix transported to the same site.

Engelmann spruce had very low germination on all treatment and soil types. Because 32.9 percent of spruce seed germinated in the stratified control, we believe most spruce seed was killed (or germination energy reduced) during the overwintering period.

Results from the forested site are inadequate as a control for this study. Conditions under the dense tree overstory are quite different than in the open bracken glades. Fewer seeds germinated in the forested treatment than in any other treatment. Because conifer seed germinated and survived on forest soil in our greenhouse bioassay tests, we feel the loss of seed viability is associated with conditions in the understory and not an inherent problem with the soil.

CONCLUSIONS AND DISCUSSION

The review of literature showed that bracken fern is a troublesome weed worldwide. It can quickly invade disturbed forests and grazed lands. Increases in bracken occurrence are attributable to human activities. Bracken is well adapted to maintaining dominance because of its unpalatability to browsing, chemical defenses against insects (Cooper-Driver 1976), ability to sprout following disturbance, and production of phytotoxins.

Bracken fern phytotoxins could reduce or eliminate other species in several ways, such as killing seed during stratification, reducing seed germination energy, reduced vigor that predisposes seedlings to other causes of mortality, or the death of plants caused by absorption of phytotoxins. Our studies on bracken fern were conducted to test the allelopathic potential of bracken fern in northern Idaho and to elucidate mechanism(s) that account for bracken dominance.

Tests conducted at our Moscow, ID, greenhouse found some statistically significant reductions in germination and growth attributable to bracken-dominated soil. Tests at a bracken fern glade showed even more striking results in that most seed died when germinated on soil dominated by bracken. The large percentage of seedlings that died helps explain the nearly total exclusion of conifers from bracken glades in northern Idaho.

Based on the results of this research, we feel an important mechanism limiting establishment of conifers in bracken glades of northern Idaho is death of germinants as the radicle penetrates the upper surface of the soil. Death probably results when the germinant absorbs phytotoxins that have accumulated in the soil over a number of years.

We hypothesize that phytotoxins are concentrated near the soil surface. This follows from finding reduced germination and growth in the greenhouse bioassay tests only in tests having bracken glade soil from the 0- to 5-cm depth. Even for the 0- to 5-cm depth, more seed survived in the greenhouse test compared to seed germinated at the study site. Mixing of the soil in the 0- to 5-cm depth may have diluted the phytotoxin, indicating that if a phytotoxic layer is present, it is thin. In addition, radicle lengths of dead seed in the seed stratification study were less than 3 cm.

Other investigators have reported that allelopathic effects are greatest near the soil surface. Gliessman and Muller (1978) collected raindrip from bracken fronds under field conditions and showed allelopathic effects using bioassay tests. They hypothesized that toxins were being concentrated in the upper soil layers where they remain even with heavy rainfall. Horsley (1977) thought that toxins from three species he investigated may be bound to the soil complex and at least 1 year is necessary for toxic plant residues to be neutralized, destroyed, or leached. Muller (1966), working in California chaparral, found that herbs were able to become established following a fire or after a layer of soil 5 cm thick was removed.

Discussion of bracken fern communities in northern Idaho would be incomplete without considering interactions with pocket gophers. The role of gophers in bracken communities is seldom mentioned in the literature. Gophers feed on forbs, grasses, shrubs, conifers, seeds, and just about any vegetation not poisonous (Teipner and others 1983). We do not know if pocket gophers feed on bracken, but few other species grow in these bracken glades where gopher populations are high.

Gophers deposit subsurface soil above ground in mounds and casts. This buries existing vegetation and, over time, would create a mosaic of microsites differing in successional status. These microsites could account for the presence of forbs, grasses, and sedges which, in turn, supply food for the gophers. These species could become established on fresh mounds, eventually dying out as bracken phytotoxins again accumulate.

Shrubs and conifers could also become established on gopher mounds. Tevis (1956) noted that an abundant red fir (*Abies magnifica*) cone crop in northern California resulted in good reproduction on ground bared by pocket gophers. (Interestingly, he noted that gopher-bared ground in nonbracken areas had "abundant" seedlings whereas seedlings on gopher-bared ground in bracken areas were "moderately common.") Seed predation by gophers and mice could account for loss of some shrub and conifer seeds, but this is unlikely to be the whole story.

An additional explanation for the lack of woody species in northern Idaho bracken glades concerns decomposition of bracken fronds under the snow. Even the casual observer is impressed with the large amount of bracken frond biomass at the Eagle Point study site. Znerold (1979) calculated frond density at 286,300 stems/ha and frond ovendry weight at 3,900 kg/ha. Each autumn fronds die, fall over, and are pressed to the earth by snow. In the spring, little evidence of old bracken fronds exists except for portions of the thick petioles that are not totally decomposed. A great deal of decomposition must take

place under the snow. Any plants crushed to the ground with bracken fronds might perish as a direct or indirect result of bracken decomposition, including succulent conifers and shrubs regenerating on pocket gopher mounds.

This possibility is speculative (and needs to be tested) but seems plausible because the few species associated with bracken fern in these glades are herbaceous (annual, biennial, or perennial plants that die back to the ground at the end of the growing season). Bracken appears to have dominated these glades for hundreds of years, and there is little evidence of succession to woody species. We have observed that shrub and conifer seed are cast into the glade. Some species of seed may be killed during stratification or the germination energy reduced below the level needed for survival. If seed does germinate, it can die as a result of absorbing phytotoxins. Seedlings surviving all of the above would then be subjected to smothering by bracken fronds and decomposition under the snow. These competitive mechanisms severely limit the establishment of woody species in bracken-dominated areas of northern Idaho.

RECOMMENDATIONS

The exploratory studies reported in this paper were designed to increase our understanding of bracken fern. Based on these results and the literature review, a list of recommendations was compiled. Additional research is needed to find answers to specific reforestation questions. For now, it should be remembered that bracken is a problem weed throughout the world, no economical solutions for its control have been found, and prevention of problems with bracken is the preferred alternative. These recommendations apply to reforestation efforts in areas where bracken has successfully invaded previously harvested stands and where bracken is present in and around stands scheduled for harvesting.

1. Recognize that allelopathy can be a major consideration when developing a silvicultural prescription. Ignoring this constraint negates investments of time and money in reforestation efforts. However, allelopathy is not a magical answer to reforestation failures.

2. Plan to regenerate stands quickly following harvest. We have found bracken rhizomes in dense forest stands adjacent to bracken glades and bracken-dominated cutover stands. Rhizome expansion coupled with colonization by spores can quickly increase bracken dominance.

3. Keep site preparation to a minimum. Hot burns or excessive scarification encourage invasion of bracken fern via spores. See Stickney (1986) for examples of bracken invasion following a severe fire in northern Idaho. Repeated burns unduly favor bracken because fires do not kill the rhizomes, which readily resprout.

4. Do not rely on natural regeneration. Plant trees as soon after harvest as possible and protect them from pocket gophers and grazing animals. Prompt planting will help ensure that trees are established before gopher populations and bracken cover build up. Planted trees should survive well if protected, but growth rates will be reduced where bracken cover is thick.

5. Exclude natural bracken glades within the stand from land to be reforested. Few, if any, trees have grown on these sites in the past. Including these areas gives a false picture of seedling density and percentage of stocked plots. Naturally occurring bracken glades are hundreds of years old and appear to be the climax vegetation. These glades are worthy of consideration as a distinct habitat type.

REFERENCES

Acsai, J.; Largent, D. L. 1983. Ectomycorrhizae of selected conifers growing in sites which support dense growth of bracken fern. Mycotaxon. 16: 509-518.

Advincula, B. A.; Woo, J. Y.; Partridge, A. D. 1983. A method for germination of western white pine seeds. Unpublished paper presented at: Western Forestry and Conservation Association Conference; 1983 December 12-14; Portland, OR. 4 p.

Bohm, B. A.; Tryon, R. M. 1967. Phenolic compounds in ferns. I. A survey of some ferns for cinnamic acid and benzoic acid derivatives. Canadian Journal of Botany. 45: 585-593.

Boyd, R. J.; Znerold, R. M. [In preparation]. The effects of bracken fern control with asulam on the subsequent performance of planted conifers in northern Idaho. Moscow, ID: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Braid, K. W. 1959. Bracken: a review of the literature. Publication 3. England: Commonwealth Bureau of Pastures and Field Crops. 69 p. Mimeo.

Brown, R. T. 1967. Influence of naturally occurring compounds on germination and growth of jack pine. Ecology. 48: 542-546.

Cody, W. J.; Crompton, C. W. 1975. The biology of Canadian weeds. 15. *Pteridium aquilinum* (L.) Kuhn. Canadian Journal of Plant Science. 55: 1059-1072.

Conway, E. 1952. Bracken - the problem plant, a review of recent conclusions about its spread and dominance. Scottish Agriculture. 31: 181-184.

Cooper-Driver, G. 1976. Chemotaxonomy and phytochemical ecology of bracken. Linnean Society Botanical Journal. 73: 35-46.

Cooper, S. V.; Neiman, K. E.; Steele, R.; Roberts, D. W. 1987. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. INT-236. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 135 p.

DeBell, D. S. 1970. Phytotoxins, new problems in forestry? Journal of Forestry. 68: 335-337.

del Moral, R.; Cates, R. G. 1971. Allelopathic potential of the dominant vegetation of western Washington. Ecology. 52: 1030-1037.

Dimock, E. J., II. 1964. Supplemental treatments to aid planted Douglas-fir in dense bracken fern. Res. Note PNW-11. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 10 p.

Evans, I. A. 1976. Relationship between bracken and cancer. Linnean Society Botanical Journal. 73: 105-112.

Fisher, R. F. 1978. Juglone inhibits pine growth under certain moisture regimes. Soil Science Society of America Journal. 42: 801-803.

Fisher, R. F. 1979. Allelopathy. In: Horsfall, J.G.; Cowling, E. B., eds. Plant disease: an advanced treatise. Vol. IV. New York: Academic Press: 313-330.

Glass, A. D. M.; Bohm, B. A. 1969. The accumulation of cinnamic and benzoic acid derivatives in *Pteridium aquilinum* and *Athyrium filix-femina*. Phytochemistry. 8: 371-377.

Gliessman, S. R. 1976. Allelopathy in a broad spectrum of environments as illustrated by bracken. Linnean Society Botanical Journal. 73: 95-104.

Gliessman, S. R.; Muller, C. H. 1972. The phytotoxic potential of bracken, *Pteridium aquilinum* (L.) Kuhn. Madroño. 21: 299-304.

Gliessman, S. R.; Muller, C. H. 1978. The allelopathic mechanisms of dominance in bracken (*Pteridium aquilinum*) in southern California. Journal of Chemical Ecology. 4: 337-362.

Hirono, I. 1981. Natural carcinogenic products of plant origin. CRC Critical Reviews in Toxicology. 8(3): 235-277.

Hirono, I.; Shibuya, C.; Shimizu, M.; Fushimi, K. 1972. Carcinogenic activity of processed bracken used as human food. Journal of the National Cancer Institute. 48: 1245-1250.

Horsley, S. B. 1977. Allelopathic inhibition of black cherry by fern, grass, goldenrod, and aster. Canadian Journal of Forest Research. 7: 205-216.

Martin, D. J. 1976. Control of bracken. Linnean Society Botanical Journal. 73: 241-246.

Muller, C. H. 1966. The role of chemical inhibition (allelopathy) in vegetation composition. Bulletin of the Torrey Botanical Club. 93: 332-351.

Page, C. N. 1982. The history and spread of bracken in Britain. Proceedings of the Royal Society of Edinburgh. 81B: 3-10.

Pamukcu, A. M.; Ertürk, E.; Yalciner, S.; Milli, U.; Bryan, G. T. 1978. Carcinogenic and mutagenic activities of milk from cows fed bracken fern (*Pteridium aquilinum*). Cancer Research. 38: 1556-1560.

Preest, D. S. 1975. Review of and observation on current methods of bracken control in forestry. Proceedings of the 28th New Zealand Weed Control Conference: 43-48.

Rice, E. L. 1979. Allelopathy—an update. The Botanical Review. 45: 15-109.

Rice, E. L. 1984. Allelopathy. Orlando, FL: Academic Press. 422 p.

Rietveld, W. J.; Schlesinger, R. C.; Kessler, K. J. 1983. Allelopathic effects of black walnut on European black alder coplanted as a nurse species. Journal of Chemical Ecology. 9: 1119-1133.

Rose, S. L.; Perry, D. A.; Pilz, D.; Schoeneberger, M. M. 1983. Allelopathic effects of litter on the growth and colonization of mycorrhizal fungi. Journal of Chemical Ecology. 9: 1153-1162.

Rymer, L. 1976. The history and ethnobotany of bracken. Linnean Society Botanical Journal. 73: 151-176.

Stewart, R. E. 1975. Allelopathic potential of western bracken. Ecology. 1: 161-169.

Stickney, P. F. 1986. First decade plant succession following the Sundance Forest Fire, northern Idaho. Gen. Tech. Rep. INT-197. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 26 p.

Taylor, J. A. 1985. Bracken encroachment rates in Britain. Soil Use and Management. 1: 53-56.

Teipner, C. L.; Garton, E. O.; Nelson, L., Jr. 1983. Pocket gophers in forest ecosystems. Gen. Tech. Rep. INT-154. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 53 p.

Tevis, L., Jr. 1956. Pocket gophers and seedlings of red fir. Ecology. 37: 379-381.

Whitehead, D. C. 1964. Identification of *p*-hydroxybenzoic, vanillic, *p*-coumaric and ferulic acids in soils. Nature. 202: 417-418.

Whittaker, R. H.; Feeny, P. P. 1971. Allelochemics: chemical interactions between species. Science. 171: 757-770.

Wilson, D.; Coyner, J.; Deckert, T. 1983. Land system inventory of the Clearwater National Forest. Orofino, ID: Clearwater National Forest. 398 p. First review draft.

Znerold, R. M. 1979. Western bracken control with asulam. Pullman, WA: Washington State University. 36 p. Thesis.

PESTICIDE PRECAUTIONARY STATEMENT

This publication reports research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended.

CAUTION: Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all pesticides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and pesticide containers.

Ferguson, Dennis E.; Boyd, Raymond J. 1988. Bracken fern inhibition of conifer regeneration in northern Idaho. Res. Pap. INT-388. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Investigations on the allelopathic potential of bracken fern in northern Idaho were conducted to gain an understanding of the mechanism(s) associated with regeneration failures. Average growth and green top weight of conifers planted in potting soil were about 1.8 and 1.6 times greater than those planted in soil from bracken glades. Greenhouse tests showed little reduction in germination of conifer and shrub seeds on soil from bracken glades. Further germination tests of conifer seeds in bracken glades showed that seeds germinated but died before shedding their seedcoats. The percentage of dead seed helps explain the virtual exclusion of conifers from bracken fern glades in northern Idaho.

KEYWORDS: *Pteridium aquilinum*, allelopathy, phytotoxins, competition

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

U.S. GOVERNMENT PRINTING OFFICE 1988-573-039/61051

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-389

March 1988

Disturbance and Recovery of Trampled Montane Grassland and Forests in Montana

David N. Cole

CLEMSON UNIVERSITY
MAY 18 1988
PUBLIC DOCUMENTS

THE AUTHOR

DAVID N. COLE prepared this report while working as a research scientist with Systems for Environmental Management, Missoula, MT. He has now joined the Intermountain Station's Wilderness Management Research Work Unit at the Forestry Sciences Laboratory on the University of Montana campus, Missoula. Dr. Cole received his B.A. degree in geography from the University of California, Berkeley, in 1972. He received his Ph.D., also in geography, from the University of Oregon in 1977. He has written many papers on the ecological effects of wilderness recreation.

ACKNOWLEDGMENTS

I greatly appreciate the contributions various people made to this project, especially those involved with the trampling. I owe special thanks to Margaret Petersen and Tim Schwecke for assistance with computer analysis of data.

RESEARCH SUMMARY

This study examined the response of five forested vegetation types and one grassland in western Montana to experimental trampling. Changes in vegetation cover, number of species, exposure of mineral soil, and soil penetration resistance were examined, as were the responses of individual species. Trampling treatments ranged from 0 to 1,600 passes per year along trampling lanes and were administered for three successive seasons. Subsequent recovery was followed for 3 years. The most significant conclusions were as follows:

1. Use/impact relationships were nonlinear (asymptotic) for all impact parameters except exposure of mineral soil. Impact increased as trampling intensity increased, rapidly at low levels of trampling and more slowly at high levels. In other words, only at low trampling intensities is amount of impact strongly influenced by differences in amount of use. Above relatively low use thresholds, further increases in use cause little further impact. Unless use levels can be kept well below these thresholds, impacts will be minimized by concentrating use. Use thresholds are estimated for each vegetation type. In the forested vegetation types, use thresholds are exceeded once a site receives 200 to 400 passes per year (I estimate this is roughly comparable to being camped on 1 to 3 nights in 1 year). In the grassland, use thresholds are not reached until sites receive 1,200 passes per year (7 to 8 nights of camping in a year).

2. The *Festuca scabrella-F. idahoensis* (rough fescue-Idaho fescue) grassland was the vegetation type most resistant to vegetation loss. The *Abies lasiocarpa/Xerophyllum tenax* (subalpine fir/beargrass) habitat type was somewhat more resistant to vegetation loss than the other forested types. Differences in vegetation loss among types are most pronounced at trampling intensities of 100 to 200 passes per year, which correspond to a night or two of camping use. Therefore, it can be particularly useful to use these more durable vegetation types where use intensities can be kept to only a night or two of camping per year.

3. The relationship between exposure of mineral soil and trampling intensity is linear. No limit was reached beyond which further use had little additional effect. Moreover, differences between habitat types were most pronounced at the heaviest trampling intensities. Where use intensities are high it makes more sense to choose a site that is resistant to exposure of mineral soil than one with resistant vegetation. Most vegetation will be lost, regardless of its resistance, but some sites can avoid soil exposure (loss of the organic horizons that cover the mineral soil) even after heavy trampling. The most resistant sites are those with thick organic horizons—for example, the *Abies lasiocarpa/Clintonia uniflora* (subalpine fir/queen's cup beadlily) habitat type—that are not located on slopes.

4. The ability of vegetation to recover was high, except where very heavy trampling removed essentially all of the vegetation. Vegetation recovery was greatest in the grassland and the most productive of the forested habitat types, *Abies lasiocarpa/Clintonia uniflora.* Recovery is influenced by both the inherent resilience of constituent species and environmental factors. Recovery of the most severely trampled lanes to the point where visual evidence of disturbance is lacking will require 5 to 10 years, depending on the habitat type. Complete recovery of all species will take much longer.

5. Recovery of a complete litter cover will occur more rapidly, within 5 years on the type most susceptible to mineral soil exposure—the grassland. Recovery of the original depth of litter was not monitored; but it would require a longer recovery period. Recovery from soil compaction was much slower; near-complete recovery will require 5 to 15 years, depending on the habitat type.

6. Deterioration generally reached near-maximum levels after two seasons of trampling. Nevertheless, all of the general conclusions formulated after just one season of trampling (Cole 1985) were corroborated in this longer term study. Other topics addressed include the trampling resistance and resilience (ability to recover) of individual species, implications for management, and suggestions for designing trampling experiments.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

CONTENTS

	Page
Introduction	1
Study Area and Methods	1
Field Methods	1
Data Analysis	3
Vegetation Responses	3
Deterioration	3
Recovery	5
What Determines Amount of Deterioration and Recovery?	10
Individual Species Responses	16
Deterioration	16
Recovery	16
Classification of Species	17
Integration of Resistance and Resilience	19
What Determines Amount of Deterioration and Recovery?	21
Responses of Soil Organic Horizons	25
Deterioration	25
Recovery	25
What Determines Amount of Deterioration and Recovery?	29
Compaction and Recovery of the Mineral Soil	30
Deterioration	30
Recovery	30
What Determines Amount of Deterioration and Recovery?	31
Management Implications	32
The FESC-FEID Habitat Type	33
The ABLA/CLUN Habitat Type	33
The ABLA/XETE Habitat Type	33
Methodological Implications	35
References	37

Disturbance and Recovery of Trampled Montane Grassland and Forests in Montana

David N. Cole

INTRODUCTION

Recreational impacts on vegetation and soils present problems for resource managers, particularly those attempting to maintain near-natural conditions in National Parks and wildernesses. In such places, human trampling is the primary recreational activity that inevitably affects vegetation and soil. The effects of most other activities can be minimal if users practice low-impact camping techniques. Research has documented the more obvious effects of trampling and has improved our understanding of how independent variables, such as type, amount, and location of use, influence amount of impact (Cole 1987b; Kuss and Graefe 1985; Liddle 1975a). Studies that carefully monitor the effects of controlled amounts of trampling have been particularly helpful.

Such studies document how rapidly the effects of trampling become obvious. The relative resistance of different environments can be assessed, and it is even possible to predict the effects of various trampling levels on vegetation and soil. By measuring the response of vegetation and soil after trampling is curtailed, recovery rates can be established. Recovery rates are likely to vary with both intensity of trampling and environment. Nevertheless it should be possible to assess the relative resilience of different environments and to predict requisite recovery periods after various amounts of trampling.

Documenting the responses of vegetation and soil to trampling will increase our understanding of these processes and also contribute to more informed management of the backcountry. Study results will improve the ability to predict the consequences of various levels of use. This capability can be used to establish use limits, to decide between dispersing or concentrating use, and to select durable locations for use. Although the results reported here are strictly applicable only to the particular vegetation and soil types that were examined, the study results should provide insights useful in other places.

This paper reports the results of experiments in which various amounts of trampling were applied to six habitat types for three successive summers. Following the cessation of trampling, recovery was monitored for 3 additional years. Objectives of these experiments were to (1) document rates of disturbance and recovery by measuring changes in vegetation cover, number of plant species, organic horizon cover, and soil compaction; (2) determine how disturbance and recovery varies with trampling intensity; and (3) determine how disturbance and recovery varies among habitat types.

STUDY AREA AND METHODS

Five forested plant communities and one grassland were selected for study. Those selected for study were representative of low to middle elevation communities in the Bob Marshall Wilderness, MT. All sites were at elevations of 4,200 to 4,400 feet (1,260 to 1,320 m). At the nearby Seeley Lake weather station, annual precipitation averages 21 inches (536 mm), with a total of 3 inches (75 mm) occurring in summer, July and August, when trampling occurred; January temperatures average 18 °F (–8 °C) and July temperatures average 63 °F (17 °C).

The grassland community, dominated by bunchgrasses, is located on a well-drained, flat upland. It represents the *Festuca scabrella-F. idahoensis* (rough fescue-Idaho fescue) habitat type of Mueggler and Stewart (1980) and will be denoted FESC-FEID hereafter. One forested community is located on a 20- to 25-percent southwest-facing slope. Characterized by medium-sized 1- to 3-foot (0.3- to 1-m) shrubs, it occupies the warmest and driest local environment of the forested communities. It is a member of the *Pseudotsuga menziesii / Symphoricarpos albus* (PSME/SYAL) (Douglas-fir/snowberry) habitat type of Pfister and others (1977). Three forested communities, the *Abies lasiocarpa / Vaccinium caespitosum* (ABLA/VACA) (subalpine fir/dwarf huckleberry), *Abies lasiocarpa / Xerophyllum tenax* (ABLA/XETE) (subalpine fir/beargrass), and *Abies lasiocarpa / Clintonia uniflora-Vaccinium caespitosum* (ABLA/CLUN-VACA) (subalpine fir/queen's cup beadlily-dwarf huckleberry phase) habitat types occupy flat terraces that are subject to frequent frosts. All three have a luxuriant undergrowth dominated by prostrate shrubs. The forested community that appears to be most productive is a member of the *Abies lasiocarpa / Clintonia uniflora* (ABLA/CLUN) (subalpine fir/queen's cup beadlily) habitat type. Soils are deep, soil moisture levels are moderately high, and the frost-free season is relatively long. In contrast to the other forested sites, this community has an overstory of large trees, mostly *Larix occidentalis* (western larch) and *Picea engelmannii* (Engelmann spruce), and an understory dominated by lush, shade-tolerant forbs. Additional information on each type is presented in table 1 and by Cole (1985). All nomenclature follows Hitchcock and Cronquist (1973).

Field Methods

Two replicate sets of experimental trampling lanes were established in each habitat type, except in the ABLA/CLUN and ABLA/CLUN-VACA types, in which only one

Table 1—Site descriptions for each habitat type[1]

Habitat type	Soil type	Mean organic horizon thickness	Mean A and B horizon thickness	Slope	Overstory mean canopy cover and species present	Understory mean total vegetation cover and dominant species
		cm	*cm*	*Pct*		
GRASSLAND TYPE						
Festuca scabrella-F. idahoensis (FESC-FEID)	Typic Haploboroll	3.0	27	0-2	None	94 percent *Festuca scabrella*, *F. idahoensis*, *Lupinus sericeus*, and *Achillea millefolium*
FOREST TYPES						
Pseudotsuga menziesii/Symphoricarpos albus (PSME/SYAL)	Eutric Glossoboralf	6.0	42	20-25	80 percent *Pseudotsuga menziesii*, *Pinus contorta*, and *Larix occidentalis*	81 percent *Calamagrostis rubescens*, *Berberis repens*, *Arnica cordifolia*, and *Spiraea betulifolia*
Abies lasiocarpa/Clintonia uniflora (ABLA/CLUN)	Eutric Glossoboralf	11.0	75	0-4	90 percent *Larix occidentalis* and *Picea engelmannii*	93 percent *Thalictrum occidentale*, *Arnica cordifolia*, *Berberis repens*, and *Smilacina stellata*
Abies lasiocarpa/Clintonia uniflora-Vaccinium caespitosum (ABLA/CLUN-VACA)	Typic Udorthent	6.0	10	0-3	90 percent *Larix occidentalis*, *Pseudotsuga menziesii*, and *Pinus contorta*	92 percent *Linnaea borealis*, *Berberis repens*, *Calamagrostis rubescens*, and *Spiraea betulifolia*
Abies lasiocarpa/Vaccinium caespitosum (ABLA/VACA)	Andic Dystrochrept	3.5	31	0-7	75 percent *Pinus contorta* and *Larix occidentalis*	90 percent *Vaccinium caespitosum*, mosses, *Xerophyllum tenax*, and *Calamagrostis rubescens*
Abies lasiocarpa/Xerophyllum tenax (ABLA/XETE)	Andic Dystrochrept	.7	28	0-2	70 percent *Pinus contorta*, *Pseudotsuga menziesii*, *Abies lasiocarpa*, and *Larix occidentalis*	93 percent *Vaccinium scoparium*, mosses, lichens, and *Xerophyllum tenax*

[1]Habitat types are a classification system based on potential climax tree species and indicator understory species (Mueggler and Stewart 1980; Pfister and others 1977). Soil types are based on the 7th Approximation (Soil Survey Staff 1975). Species nomenclature follows Hitchcock and Cronquist (1973). Tree species and understory dominants are listed in order of decreasing mean cover.

set was established. Each set of treatments consisted of 17 lanes, each 1 foot (0.3 m) wide and about 16 feet (5 m) long.

Treatments were randomly assigned to each lane. One treatment was a control and was never trampled. On the other lanes, we varied both the total number of passes per year and the number of days per year when trampling was applied. Whether trampling was concentrated at one time or spread out over the summer had no consistent effect (Cole 1985), however, so all treatments were considered as a simple incremental series. One lane each received 5, 15, 25, 40, 75, 80, 100, 200, 400, 600, 800, 900, 1,200, or 1,600 passes per season and two lanes received 300 passes. Each pass was a one-way walk, at a natural gait, along the lane. The weight of tramplers varied from about 130 to 190 pounds (60 to 90 kg); all wore lug-soled boots.

Trampling treatments were administered between late June and mid-August in 1981, 1982, and 1983. Initial measurements were taken on all lanes in June 1981, prior to any trampling. Followup measurements were taken in June 1982, 1983, and 1984, and in August 1981, 1982, 1983, 1984, 1985, and 1986. The plots in the ABLA/VACA type were disturbed by logging during the period after trampling ceased; consequently, long-term recovery could not be evaluated in this type.

Measurements were taken in four 0.66- by 1.64-foot (2- by 5-dm) subplots placed in the center of each lane, 3.3, 6.5, 9.8, and 13.1 feet (1, 2, 3, and 4 m) from one end of the lane. In each subplot the cover of total ground cover vegetation, exposed mineral soil (without either overlying vegetation or organic material), each vascular plant

species, all mosses, and all lichens, was estimated to the nearest percentage if under 10 percent, or in 10-percent coverage classes if between 10 and 100 percent. Soil compaction was measured with a pocket soil penetrometer once in each subplot, below the unconsolidated surface organic litter horizon. For additional information on the layout of the experiments, see Cole (1985).

Data Analysis

Change in vegetation cover was calculated by two different methods. Both are based on the concept of relative cover (Bayfield 1979), which refers to the proportion of the original cover that survives after trampling, corrected by a factor that accounts for changes on the control lanes. The first measure, "vegetation cover," is based on a single estimate of the total cover of vegetation in each subplot. This provides a measure of the proportion of the ground covered by vegetation. It is calculated as follows:

$$\text{Vegetation cover} = \frac{\text{surviving cover on each trampled subplot}}{\text{initial cover on each trampled subplot}} \times \text{cf} \times 100\%$$

$$\text{where cf} = \frac{\text{mean initial cover on control subplots}}{\text{mean surviving cover on control subplots}}$$

and cover is a single estimate of vegetation cover on the subplot.

A more three-dimensional measure of vegetation is provided by what I call "species cover." This relative cover measure is based on the sum of the coverages of all species on the subplot. This sum often exceeded 100 percent because different species form overlapping layers. Species cover provides a more meaningful measure of how much vegetation has been lost as a result of trampling, because in some situations a substantial quantity of vegetation can be lost before vegetation cover declines from 100 percent. Species cover is calculated as follows:

$$\text{Species cover} = \frac{\text{surviving cover on each trampled subplot}}{\text{initial cover on each trampled subplot}} \times \text{cf} \times 100\%$$

$$\text{where cf} = \frac{\text{mean initial cover on control subplots}}{\text{mean surviving cover on control subplots}}$$

and cover is the sum of the percent covers of all vascular species, mosses, and lichens on the subplot.

Species persistence is a measure of vegetation response that reflects changes in the number of species on each subplot. It is calculated as follows:

$$\text{Species persistence} = \frac{\text{number of species on each subplot after trampling}}{\text{initial number of species on each subplot}} \times 100\%$$

Two measures of soil response were used. The first, increase in mineral soil exposure, is concerned with the loss of surface soil organic horizons. It is a measure of the proportion of ground surface on which both vegetation and organic horizons have been lost, exposing bare mineral soil. The formula is:

$$\text{Increase in mineral soil (MS)} = \text{MS (\% cover) after trampling} - \text{initial MS}$$

Soil compaction was assessed by measuring the increase in resistance of the soil to penetration. It was calculated as follows:

$$\text{Increase in penetration resistance (PR)} = \text{PR on each trampled subplot} - \text{mean PR on control subplots}$$

All initial (pretreatment) measurements refer to those taken in mid-June 1981 prior to trampling. Species persistence and increase in mineral soil exposure values were not corrected by a factor related to change on controls, as other measures were. No mineral soil was exposed on controls, so correction was unnecessary. For species persistence it seemed more appropriate to not modify values on the basis of control changes, because even under undisturbed conditions changes in number of species exhibited pronounced local variability. Therefore, changes on controls were not necessarily an accurate reflection of what would have occurred on treated lanes in the absence of trampling. Increases in penetration resistance were not pre- and posttreatment comparisons, as other measures were, because resistance varies with soil moisture and moisture varied greatly between early and late summer and between years. Instead, change was inferred by comparing trampled lanes to controls.

VEGETATION RESPONSES

Deterioration

By August 1983, three successive summers of trampling had reduced vegetation cover on all the habitat types. Cover loss increased as trampling intensity increased (table 2). The relationship between trampling intensity and cover loss was not linear, however; an asymptotic model best describes the relationship. The increase in cover loss with increased trampling intensity is rapid at low levels of trampling but diminishes at higher levels (fig. 1).

Table 2—Species cover[1] after three seasons of trampling

Number of passes per year	Habitat type						All habitat types
	FESC-FEID	ABLA/ XETE	ABLA/ VACA	PSME/ SYAL	ABLA/ CLUN-VACA	ABLA/ CLUN	
	Percent						
0	100[a]	100[a]	100[a]	100[a]	100[a]	100[a]	100
5	94[a]	91[a]	81[ab]	86[ab]	67[bc]	58[c]	83
15	87[a]	85[a]	76[ab]	69[ab]	67[ab]	59[b]	76
25	82[a]	65[ab]	57[b]	55[b]	52[b]	53[b]	62
40	85[a]	65[b]	52[bc]	37[c]	39[c]	50[bc]	57
75	91[a]	45[b]	37[b]	32[b]	38[b]	27[b]	47
80	67[a]	39[b]	34[b]	41[b]	46[b]	22[b]	43
100	70[a]	44[b]	40[b]	20[c]	21[c]	17[c]	39
200	69[a]	31[b]	7[c]	5[c]	5[c]	6[c]	23
300	58[a]	18[b]	11[b]	13[b]	5[b]	9[b]	21
400	49[a]	11[b]	12[b]	5[b]	6[b]	3[b]	16
600	35[a]	15[b]	10[b]	9[b]	0[b]	4[b]	14
800	34[a]	10[b]	4[b]	1[b]	1[b]	2[b]	10
900	35[a]	8[b]	5[b]	3[b]	1[b]	3[b]	11
1,200	14[a]	7[b]	2[b]	2[b]	0[b]	1[b]	5
1,600	16[a]	7[b]	2[b]	1[b]	0[b]	0[b]	5
Mean of all treatments	62[a]	39[b]	32[c]	29[c]	27[c]	25[c]	37

[1]Species cover is the proportion of original vegetational cover present after trampling (based on the sum of the coverages of each species), adjusted for changes on controls. Any two cover loss values in the same row followed by the same letter are not significantly different (Duncan's multiple range test, $p = 0.05$).

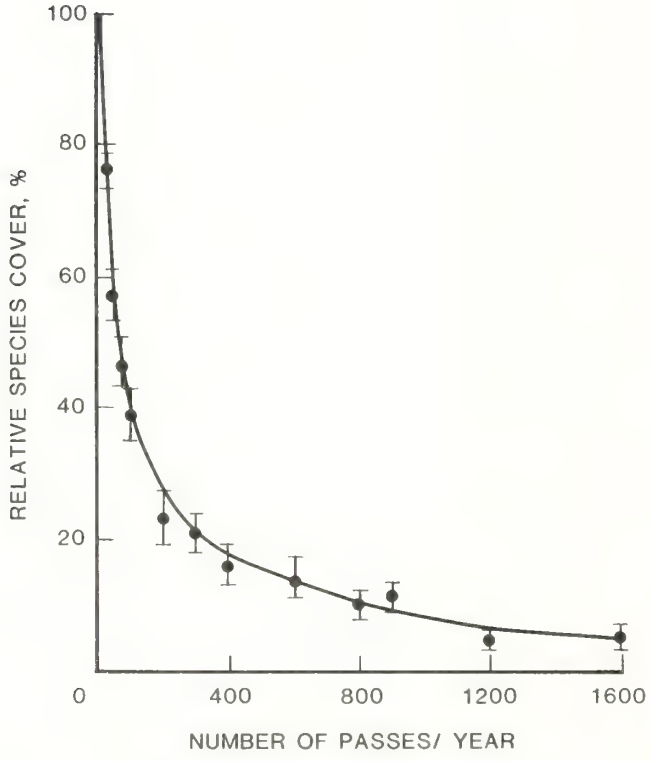


Figure 1—Relationship between trampling intensity and species cover after three seasons of trampling. Species cover is the proportion of original vegetation cover present after trampling (based on the sum of the coverages of each species), adjusted for changes on controls. Data are the mean of all habitat types. Vertical bars are ±1 standard error.

Figure 2—The appearance of the lane with 1,600 passes per year, in the PSME/SYAL habitat type, after the second year of trampling. Vegetational cover is 0 percent; mineral soil exposure is 7 percent.

There were pronounced differences between habitat types, particularly between the grassland and the forests (table 2). In all the forested types, more than 50 percent of the species cover was lost once trampling intensities exceeded 40 passes per year. Only in the most resistant forested type, ABLA/XETE, did more than 15 percent cover survive intensities of more than 100 passes per year (fig. 2). The FESC-FEID grassland was much more resistant; in this type, 50 percent of the cover was lost only where trampling intensity exceeded 300 passes per year.

The general relationship between vegetation cover (based on a single estimate of total vegetation cover) and trampling intensity was also asymptotic. The primary difference between vegetation and species cover (both posttreatment relative cover measures) was that higher levels of vegetation cover survived each trampling intensity. Because loss of one layer of vegetation may not result in a reduction in the areal coverage of vegetation, the volume of vegetation is reduced more rapidly than the areal coverage; therefore, species cover is the more sensitive measure of change. Differences between these two measures were most pronounced on the most lightly trampled lanes. For example, in the ABLA/CLUN type vegetation cover on the 15-pass lane was 89 percent, while species cover was only 59 percent. Thus, with light trampling, considerable vegetation can be lost, despite the fact that total vegetation cover remains near pretreatment levels. With heavy trampling, however, both species and vegetation cover decline dramatically.

The number of passes required to reduce relative vegetation cover to 50 percent has been suggested as an indicator of susceptibility to trampling (Liddle 1975b). In the resistant FESC-FEID grassland, only lanes trampled at least 600 times per year had less than 50 percent vegetation cover. In ABLA/XETE, lanes trampled 300 times per year had less than 50 percent cover. The other four forested types were still more susceptible. The number of passes per year required to reduce this relative measure of cover to 50 percent was 200 in ABLA/VACA, 100 in ABLA/CLUN-VACA and PSME/SYAL, and 75 in ABLA/CLUN.

The proportion of species that survived trampling (species persistence) also declined as trampling intensity increased (table 3). Again the general relationship was asymptotic and the habitat types that were most susceptible to loss of cover were most susceptible to loss of species. Compared with species and vegetation cover, a larger proportion of species survived any given level of trampling. Differences among habitat types were less pronounced than for species and vegetation cover and were most pronounced at higher trampling intensities—600 to 900 passes per year.

Recovery

Considerable recovery occurred on all habitat types after trampling was curtailed (fig. 3). For all types and all trampling intensities, the mean increase in species cover the first year after trampling ceased was 17 percent; mean

Table 3—Species persistence[1] after three seasons of trampling

Number of passes per year	Habitat type						All habitat types
	FESC-FEID	ABLA/XETE	ABLA/CLUN-VACA	ABLA/VACA	ABLA/CLUN	PSME/SYAL	
	Percent						
0	83[b]	109[a]	104[ab]	101[ab]	102[ab]	95[ab]	98
5	90[a]	108[a]	97[a]	91[a]	81[a]	92[a]	98
15	69[b]	103[a]	84[ab]	87[ab]	94[ab]	92[ab]	88
25	77[b]	106[a]	83[ab]	74[b]	94[ab]	75[b]	84
40	78[bc]	97[a]	85[ab]	82[ab]	85[ab]	64[c]	81
75	80[a]	80[a]	78[a]	58[a]	73[a]	68[a]	72
80	77[a]	78[a]	81[a]	66[ab]	47[b]	80[a]	73
100	66[a]	75[a]	71[a]	61[a]	62[a]	60[a]	66
200	84[a]	61[ab]	36[b]	35[b]	48[b]	35[b]	51
300	70[a]	46[b]	46[b]	46[b]	43[b]	36[b]	48
400	55[a]	32[b]	35[b]	29[b]	11[b]	26[b]	33
600	42[a]	27[b]	3[c]	17[bc]	14[bc]	26[b]	24
800	49[a]	37[a]	13[b]	9[b]	13[b]	11[b]	24
900	37[a]	26[a]	5[b]	17[b]	9[b]	13[b]	20
1,200	35[a]	13[b]	10[b]	6[b]	8[b]	11[b]	5
1,600	34[a]	14[b]	0[b]	17[b]	5[b]	7[b]	5
Mean of all treatments	66[a]	62[a]	52[b]	49[c]	49[b]	49[b]	55

[1]Species persistence is the proportion of the original number of species still present after trampling. Any two values in the same row followed by the same letter are not significantly different (Duncan's multiple range test, $p = 0.05$).

Figure 3—The same lane as in figure 2, 3 years after trampling ceased. Vegetational cover is 29 percent, mostly *Berberis repens*, *Aster conspicuus*, and *Arnica cordifolia*; mineral soil exposure is 0 percent.

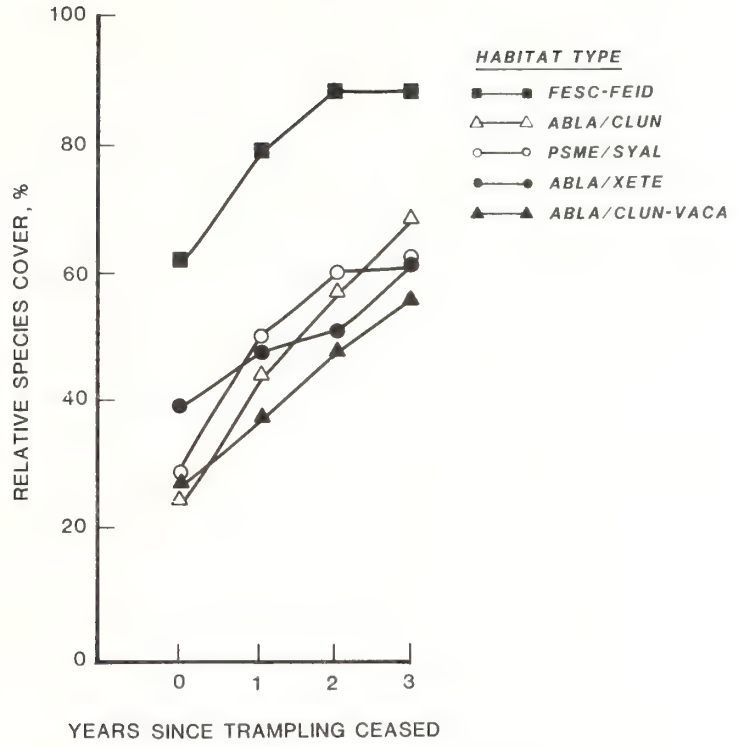


Figure 4—Differences among habitat types in vegetation recovery following the cessation of trampling. Species cover is the proportion of original vegetational cover present at some future date (based on the sum of the coverages of each species), adjusted for changes on controls. Data are the mean of all trampling intensities. All standard errors were between 0.8 and 2.3 percent.

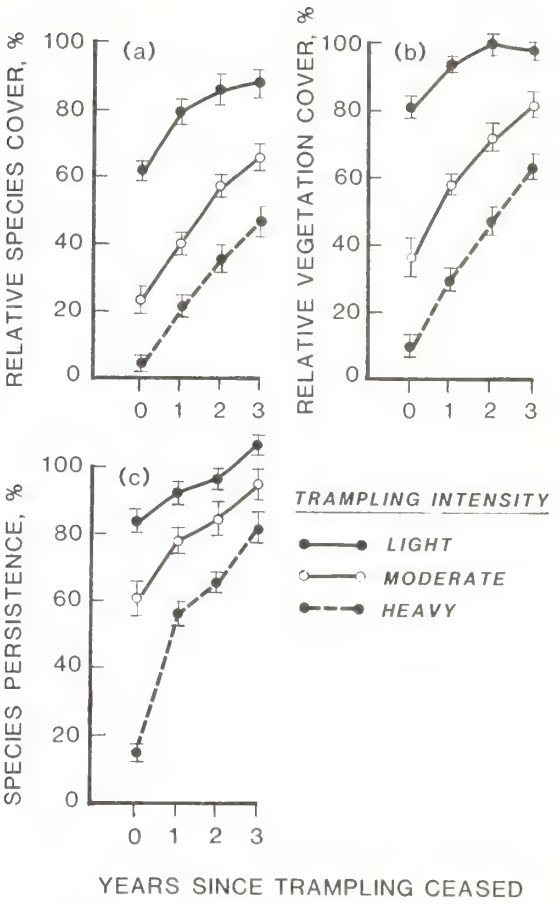


Figure 5—Recovery of (a) species cover, (b) vegetation cover, and (c) species persistence following cessation of trampling at various intensities. See text for definitions. Values for light trampling were median values for lanes with 15, 25, and 40 passes per year, for all habitat types. Values for moderate and heavy trampling were median values for lanes with 100, 200, and 300 passes per year and lanes with 900, 1,200, and 1,600 passes per year, respectively. Vertical bars are ±1 standard error.

increases the 2 following years were 11 and 7 percent. Recovery rates differed among habitat types and with trampling intensity, however (fig. 4).

Figure 5 shows the amount of vegetation recovery each year following curtailment of various levels of trampling. In these graphs and many others in this report, responses to given levels of trampling are expressed as the median of three proximate trampling intensities. For example, light trampling is the median of the lanes with 15, 25, and 40 passes per year. Moderate and heavy trampling are the medians of the lanes with 100, 200, and 300 passes per year and of the lanes with 900, 1,200, and 1,600 passes per year, respectively. This was done because the responses of individual lanes were sometimes affected by an unusual predominance of either resistant or susceptible species, a condition that was impossible to control. Using the median of three trampling lanes resulted in more consistent responses.

As figures 5a and 5b show, recovery rates are constant until species cover approaches 80 percent and vegetation cover approaches 95 percent; above these levels, recovery is less rapid. Recovery of a near-complete vegetation cover occurs rapidly, while development of multilayered vegetation occurs more slowly. Once total cover approaches 100 percent, competition probably slows further increases in vegetation cover.

Recovery of species on the most heavily trampled lanes was most rapid during the first year following the cessation of trampling (fig. 5c). Otherwise, rates were relatively constant, regardless of year since trampling ceased or trampling intensity. Rates did not level off until more than 100 percent of the original species were present. Apparently light trampling can lead to an increase in species richness, a result that provides support for Grime's (1973) hypothesis that maximum species richness occurs at moderate levels of disturbance. Light trampling opens up the cover so new species can colonize, but most of the original species also remain capable of regenerating. Although in many situations an increased species richness might be desirable, from the point of view of preserving natural conditions this represents a human-caused—and therefore undesirable—change.

Despite these general patterns, the response of each habitat type was unique (figs. 6 and 7). In the FESC-FEID grassland, recovery was rapid (tables 4 and 5). Three years after trampling ceased, a path of obviously disturbed vegetation was evident only on the lanes that received

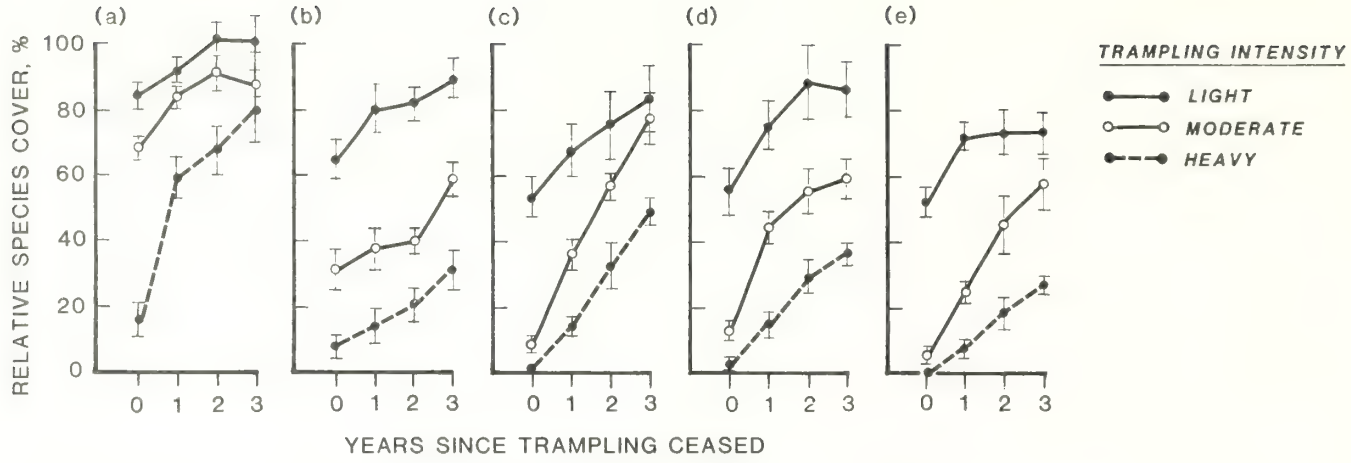


Figure 6—Recovery of species cover following the cessation of trampling. Species cover is the proportion of original vegetational cover present (based on the sum of the coverages of each species), adjusted for changes on controls. Cover values for light trampling were median values for lanes with 15, 25, and 40 passes per year. Cover values for moderate and heavy trampling were median values for lanes with 100, 200, and 300 passes per year and lanes with 900, 1,200, and 1,600 passes per year, respectively. Vertical bars are ±1 standard error. Habitat types are (a) *Festuca scabrella-F. idahoensis,* (b) *Abies lasiocarpa/Xerophyllum tenax,* (c) *Abies lasiocarpa/Clintonia uniflora,* (d) *Pseudotsuga menziesii/ Symphoricarpos albus,* and (e) *Abies lasiocarpa/Clintonia uniflora-Vaccinium caespitosum.*

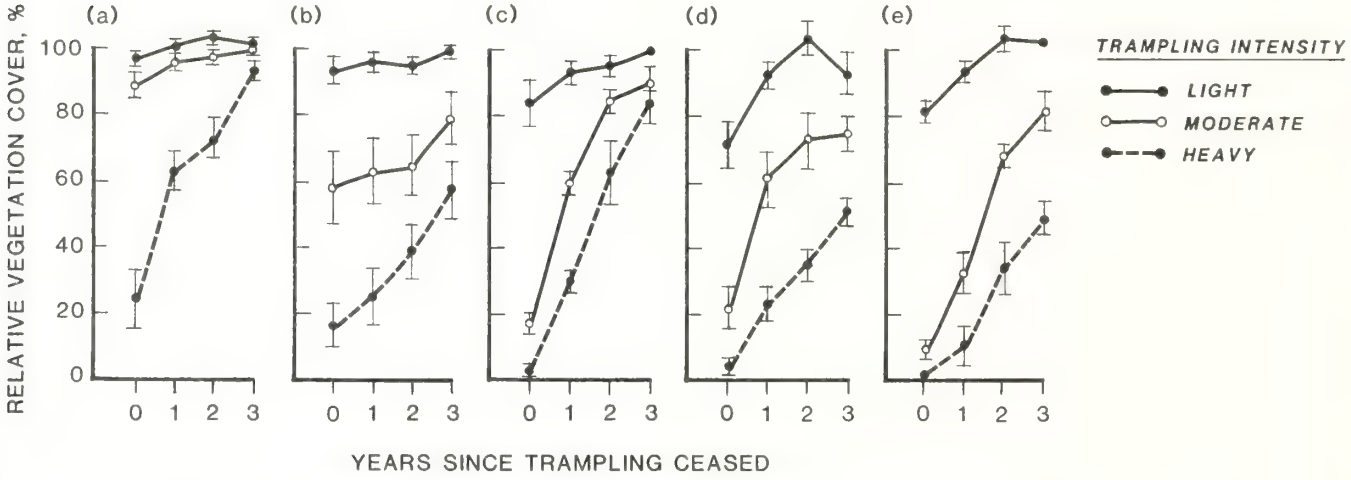


Figure 7—Recovery of vegetation cover following the cessation of trampling. Vegetation cover is the proportion of original cover present (based on a single estimate), adjusted for changes on controls. Cover values for light trampling were median values for lanes with 15, 25, and 40 passes per year. Cover values for moderate and heavy trampling were median values for lanes with 100, 200, and 300 passes per year, and lanes with 900, 1,200, and 1,600 passes per year, respectively. Vertical bars are ±1 standard error. Habitat types are (a) *Festuca scabrella-F. idahoensis,* (b) *Abies lasiocarpa/Xerophyllum tenax,* (c) *Abies lasiocarpa/Clintonia uniflora,* (d) *Pseudotsuga menziesii/Symphoricarpos albus,* and (e) *Abies lasiocarpa/Clintonia uniflora-Vaccinium caespitosum.*

Table 4—Species cover[1] 3 years after trampling ceased

Number of passes per year	Habitat type					All habitat types
	FESC-FEID	ABLA/CLUN	ABLA/XETE	PSME/SYAL	ABLA/CLUN-VACA	
	Percent					
0	100[a]	100[a]	100[a]	100[a]	100[a]	100
5	89[ab]	75[bc]	102[a]	101[a]	63[c]	90
15	110[a]	90[ab]	109[a]	87[ab]	77[b]	98
25	101[a]	74[bc]	90[ab]	67[c]	73[bc]	83
40	98[a]	83[a]	89[a]	86[a]	69[a]	87
75	99[a]	73[b]	79[b]	66[b]	73[b]	79
80	94[a]	82[a]	73[a]	92[a]	77[a]	85
100	87[a]	81[a]	83[a]	72[a]	72[a]	80
200	87[a]	42[b]	59[b]	48[b]	43[b]	60
300	93[a]	77[ab]	44[c]	59[bc]	58[bc]	66
400	88[a]	62[b]	50[b]	47[b]	51[b]	60
600	71[a]	76[a]	49[ab]	66[a]	32[b]	60
800	76[a]	46[ab]	33[b]	33[b]	42[ab]	41
900	78[a]	53[b]	39[b]	42[b]	27[b]	50
1,200	80[a]	47[b]	31[b]	36[b]	26[b]	46
1,600	87[a]	49[b]	31[b]	25[b]	23[b]	45
Mean of all treatments	89[a]	70[b]	65[bc]	64[bc]	57[c]	70

[1]Species cover is the proportion of original vegetation cover present at some future date (based on the sum of the coverages of each species), adjusted for changes on controls. Any two values in the same row followed by the same letter are not significantly different (Duncan's multiple range test, $p = 0.05$).

Table 5—Species persistence[1] 3 years after trampling ceased

Number of passes per year	Habitat type					All habitat types
	FESC-FEID	ABLA/CLUN	PSME/SYAL	ABLA/CLUN-VACA	ABLA/XETE	
	Percent					
0	120	106	107	129	106	113
5	109	105	115	104	105	108
15	88[a]	123[b]	100[a]	107[ab]	105[ab]	102
25	108	111	105	103	108	107
40	105	117	114	99	112	110
75	107	105	108	100	110	107
80	110	94	110	108	90	103
100	85	101	104	108	88	95
200	118[a]	95[ab]	85[ab]	92[ab]	78[b]	94
300	119[a]	100[ab]	99[b]	86[b]	81[b]	98
400	97[a]	87[ab]	67[b]	88[ab]	65[b]	79
600	92	97	89	82	81	88
800	88	93	75	69	75	80
900	106[a]	73[b]	73[b]	66[b]	78[b]	82
1,200	106[a]	102[ab]	83[bc]	81[bc]	71[c]	88
1,600	107[a]	73[b]	69[b]	63[b]	73[b]	79
Mean of all treatments	105[a]	99[ab]	94[bc]	92[bc]	89[c]	96

[1]Species persistence is the proportion of the original number of species still present at some future date. Any two values in the same row followed by the same letter are not significantly different (Duncan's multiple range test, $p = 0.05$). Rows with no letters have no significant differences.

1,200 and 1,600 passes per year, and the only visual evidence of trampling was abraded clumps of *Festuca scabrella* that had not completely recovered.

Estimates of the period of time required for recovery are of considerable interest. One possible set of criteria for near-complete recovery would be as follows: >95 percent vegetation cover; >90 percent species persistence; >80 percent species cover; and no evident trail. On any lane that met these criteria there would be no visible evidence of disturbance and species cover and composition would be approaching original conditions. Using this definition, recovery of the FESC-FEID type was nearly complete within 1 year on lanes trampled 200 times per year or less, and within 3 years on most lanes trampled 900 times per year or less. Extrapolation of results, which must be interpreted cautiously (recovery rates are not linear), suggests near-complete recovery of the most severely trampled lanes in about 4 years after the cessation of trampling.

Two additional limitations of this study must be kept in mind when interpreting these recovery rates. First, trampling continued for only 3 years, a short period of time compared with how long use has occurred on most recreation sites. Second, narrow trampling lanes were bordered by relatively undisturbed buffer strips that provided sources of seed and vegetative reproduction. Both of these limitations contribute to more rapid recovery than would occur on typical recreation sites.

The ABLA/XETE type recovered steadily but slowly. Cover was low after 3 years of recovery despite the fact that more cover survived trampling on this habitat type than any other forested type (table 4). Three years after trampling had ceased, a path was still evident on lanes trampled as infrequently as 200 times per year. Near-complete recovery occurred in 1 year only on lanes trampled 40 times per year or less; recovery in 3 years usually occurred on lanes trampled 100 times per year or less. Near-complete recovery of the most severely trampled lanes apparently will require about 10 years.

In contrast, ABLA/CLUN recovered rapidly over the 3-year period. ABLA/CLUN was the type most susceptible to vegetation loss, but it was also the most resilient type. It had the least cover immediately after trampling, but 3 years later it had more cover than any of the forested types, and the difference between it and the FESC-FEID grassland declined over the recovery period. Three years after trampling ceased, a path was discernible only on the lanes with 1,200 and 1,600 passes per year. Near-complete recovery did not occur on any lane in 1 year, but occurred within 3 years on lanes trampled 100 times per year or less. Despite the rapid disappearance of visual evidence of impact, species cover values remain depressed. Vegetational cover rapidly recovered, but redevelopment of the original structure of several overlapping layers of vegetation—the sum of coverages of all species exceeded 200 percent on the control—will take much longer. On the most severely trampled lanes, visual evidence of disturbance is likely to disappear within 5 years, but it is likely to take 7 to 8 years for species cover to reach 80 percent.

The other habitat types responded in a manner that was intermediate to the responses of ABLA/XETE and ABLA/CLUN. They were generally less resistant and more resilient than ABLA/XETE, but they were more resistant and less resilient than ABLA/CLUN.

What Determines Amount of Deterioration and Recovery?

Both of the controlled variables, trampling intensity and habitat type, had a substantial influence on amount of deterioration. FESC-FEID is by far the most resistant habitat type, and ABLA/XETE is significantly more resistant than the other forested types. At a trampling intensity of 400 passes per year, for example, FESC-FEID retained 15 times the proportion of cover and five times the proportion of species that ABLA/CLUN did. The ranking of habitat types according to resistance holds at all trampling intensities, although differences were most substantial at trampling intensities of about 100 to 300 passes per year (table 2); differences in resistance to loss of species were most substantial at intensities of 600 to 900 passes per year (table 3).

Differences between habitat types modify the general relationship between deterioration rate and trampling intensity. On each habitat type, cover and number of species declined with increasing trampling intensity before reaching a limit beyond which further increases in trampling intensity cause little additional cover loss. This limit varies greatly between types. It is reached after 1,200 passes per year in FESC-FEID, 400 passes per year in ABLA/XETE, and 200 passes per year in the other types. This limit is significant because it defines the level below which decreases in amount of trampling are likely to have positive benefits—less cover loss—and above which increases in trampling are likely to have little negative effect.

When evaluating recovery, two different measures are needed. First, recovery can be evaluated by comparing conditions following recovery to original conditions. Maximum recovery, using this measure, would occur on the site that most closely approximates original undisturbed conditions. I will refer to this as the **level** of recovery. The problem with relying entirely on this measure is that a resistant site might have a high recovery level without recovering at all. A high recovery level can be simply a result of little impact occurring following treatment. Alternatively, recovery can be evaluated by comparing conditions following recovery to conditions immediately following disturbance. Using this measure, maximum recovery would occur on the site with the greatest difference between conditions immediately following disturbance and conditions following a recovery period. I will refer to this as the **amount** of recovery. This measure is closer to the concept of recovery. The problem with this measure is that resistant sites have a lower potential for recovery because amount of recovery is limited by how much impact occurred. Interpretation of recovery is aided by using both measurements.

The relationship between trampling intensity and recovery is complex. In figure 5a there is an obvious pattern of increasing deterioration (species cover after trampling) and decreasing recovery **level** (species cover 3 years after trampling ceased) with increasing trampling intensity. Those lanes that were trampled most lost the most cover and remained most devegetated 3 years later. This relationship applies across all habitat types, reflecting the strong relationship between trampling intensity and deterioration.

Amount of recovery (the difference in species cover before and after the 3-year recovery period) was not influenced by trampling intensity, however, except at the lowest trampling intensities (< 75 passes per year)—intensities at which amount of recovery was low. This reflects the tendency for amount of recovery to decrease after species cover approaches 80 percent.

When we examine the response of individual habitat types, there are more pronounced differences in amount of recovery related to differences in trampling intensity (fig. 6). In ABLA/XETE, amount of recovery is similar at all trampling intensities; recovery is greatest with heavy trampling in FESC-FEID and recovery is greatest with moderate trampling in ABLA/CLUN, PSME/SYAL, and ABLA/CLUN-VACA. Although the trampling intensity at which recovery is maximized differs among types, the level of deterioration at which recovery is maximized is more consistent. With the exception of ABLA/XETE, amount of recovery is always greatest where 80 to 95 percent of the cover has been lost. Lanes with both more and less deterioration than this recovered less. This leads to the somewhat surprising conclusion that the potential for recovery increases with cover loss, until loss reaches 80 to 95 percent, and then decreases.

In sum, trampling intensity influences deterioration directly, but its effect on recovery is indirect. Within any habitat type, deterioration increases and level of recovery decreases on more heavily trampled lanes. The capacity to recover, however, is more closely related to the amount of surviving vegetation than to trampling intensity. Amount of recovery is greatest where most but not all vegetation has been lost. The ability to recover can be high even after heavy trampling, except where trampling is so severe that all cover is removed. Vegetation retains a high recovery potential, even in the face of increasing levels of trampling, until this threshold is exceeded.

Habitat type directly affects both deterioration and recovery. Data that depict differences among habitat types in deterioration, recovery level, and amount of recovery are plotted in figure 8. This graphic is an extension of one first suggested by Bayfield (1979). The left vertical axis shows species cover 3 years after trampling ceased, providing a measure of recovery level. The bottom axis shows species cover immediately after the third season of trampling, a measure of how much cover has been lost. Amount of recovery is the perpendicular distance of a point from the diagonal line of equal cover both immediately after trampling and after 3 years of recovery. Lines for 0, 20, 40, 60, and 80 percent recovery have been drawn in and are labeled along the right vertical axis. The response of each habitat type to light, moderate, and heavy trampling is indicated. Relative levels of resistance and resilience are summarized in figure 9. The divergent responses of ABLA/CLUN, FESC-FEID, and ABLA/XETE are illustrated in figures 10, 11, and 12.

The relative resistance and resilience of each habitat type, in terms of vegetation cover and species persistence, are similar to that for species cover. As with species cover, recovery of vegetation cover is related more closely to amount of surviving vegetation than to trampling intensity (figs. 5 and 7). The ability to recover remains high, despite increased trampling (amount of recovery actually increases), until trampling is so heavy that surviving cover is only 5 to 10 percent. Beyond this threshold, the ability to recover declines.

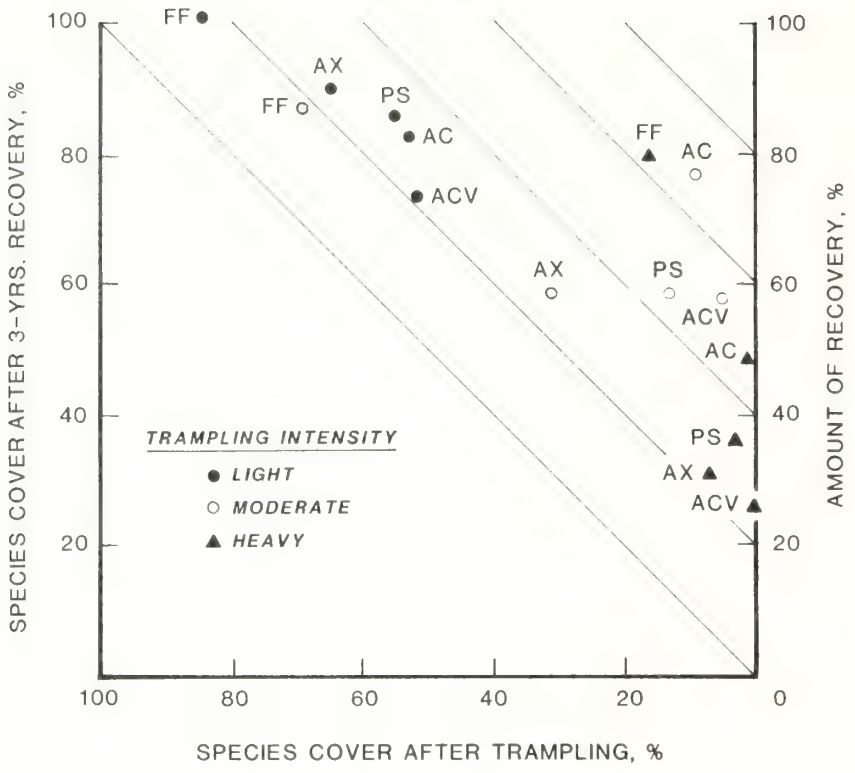


Figure 8—Species cover loss and recovery following light, moderate, and heavy trampling in each habitat type. Species cover is the proportion of original vegetational cover present (based on the sum of the coverages of each species), adjusted for changes on controls. Amount of recovery, the diagonal lines with values along the right axis, is the increase in species cover that occurred during the 3 years following the cessation of trampling. Habitat types are *Festuca scabrella-F. idahoensis* (FF), *Abies lasiocarpa/ Xerophyllum tenax* (AX), *Abies lasiocarpa/ Clintonia uniflora* (AC), *Pseudotsuga menziesii/ Symphoricarpos albus* (PS), and *Abies lasiocarpa/Clintonia uniflora-Vaccinium caespitosum* (ACV). Trampling intensities are light (median of 15, 25, and 40 passes per year), moderate (median of 100, 200, and 300 passes per year), and heavy (median of 900, 1,200, and 1,600 passes per year).

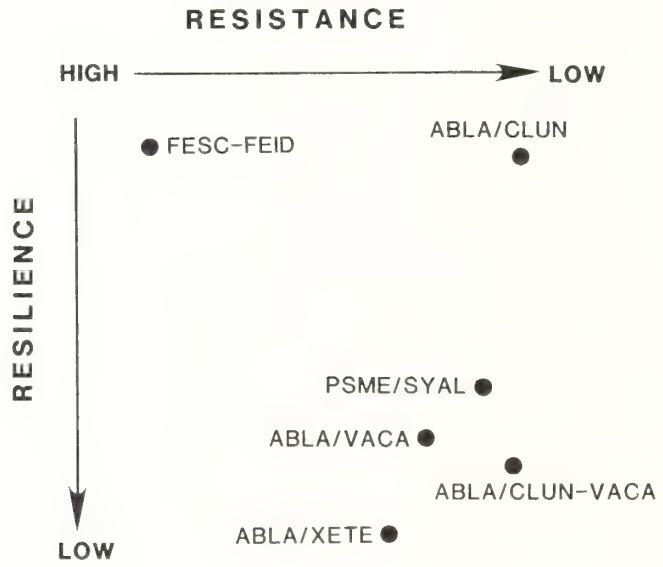
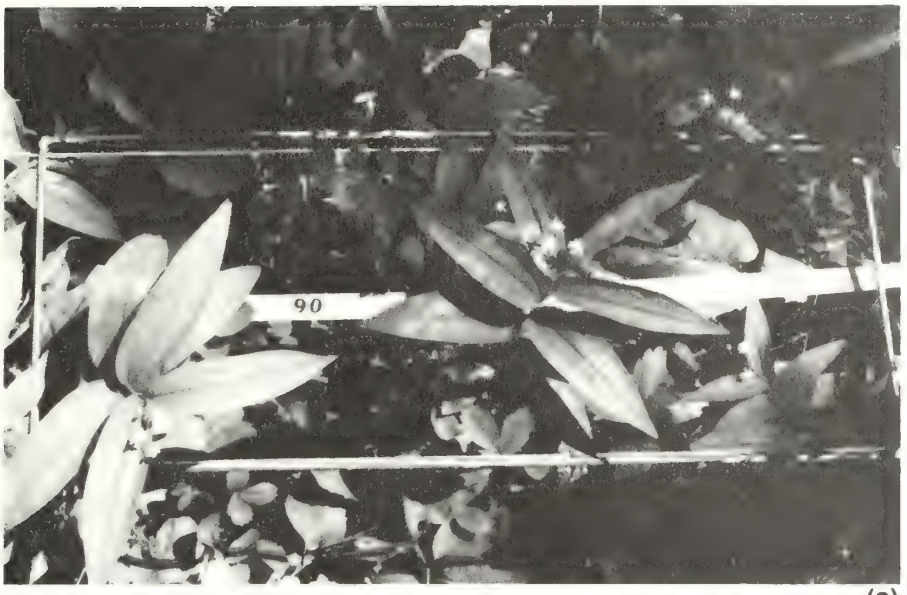
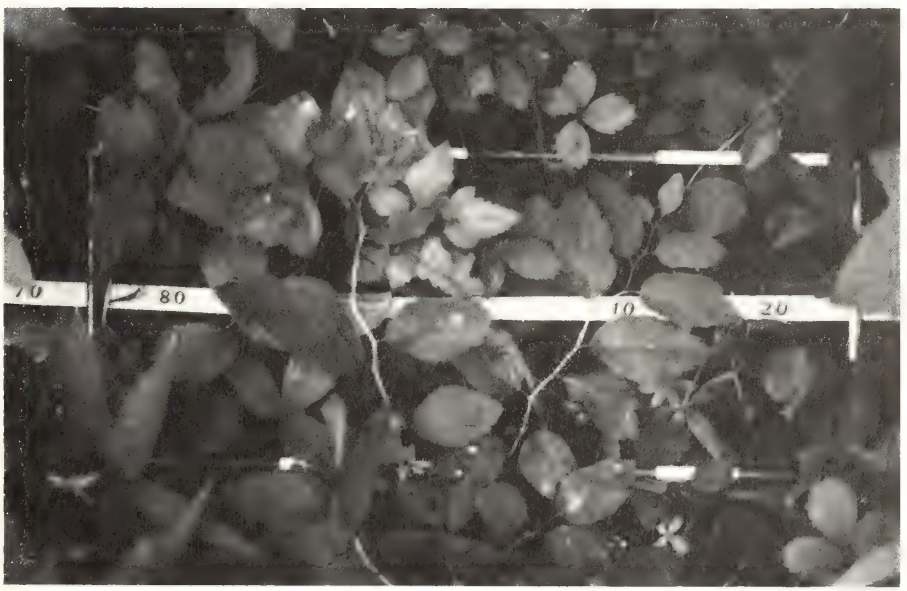


Figure 9—The relative resistance and resilience of each habitat type.



(a)

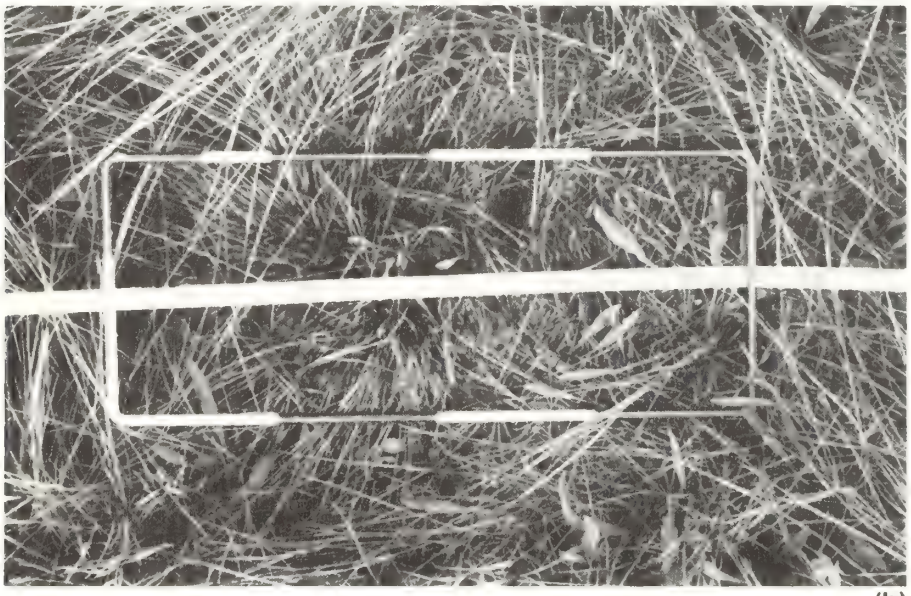
(b)



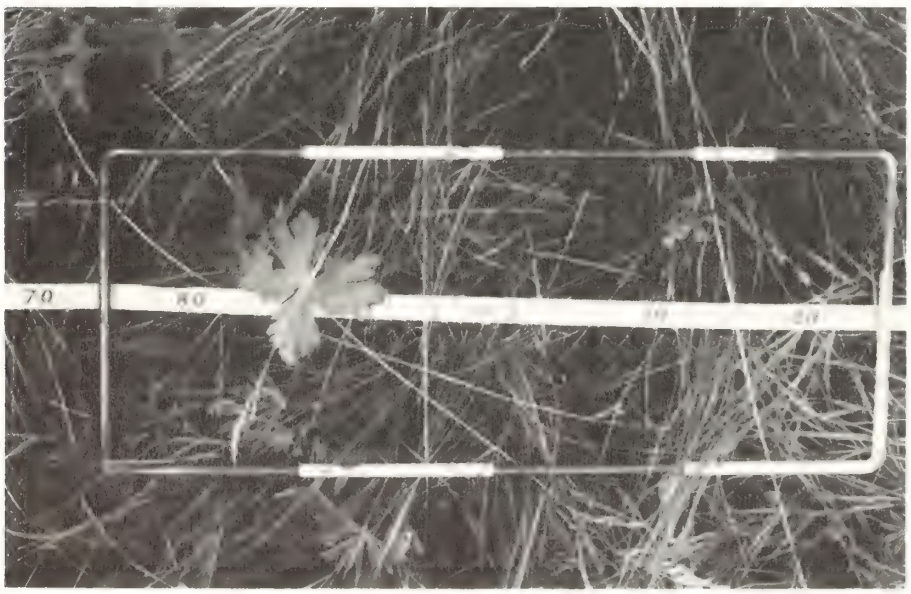
(c)

Figure 10—Response of the *Abies lasiocarpa/Clintonia uniflora* habitat type to 300 passes per year. The combined cover of all 11 species was 128 percent before trampling (a). After 3 years of 300 passes per year, only six species survived and cover was 15 percent (b). Three years after trampling ceased, 12 species were found on the subplot and combined cover was 198 percent (c). The most abundant species before trampling (*Smilacina stellata* and *Thalictrum occidentale*) were virtually absent 6 years later, when the most abundant species were *Spiraea betulifolia* and *Arnica latifolia*. This illustrates the low resistance/high resilience response.

(a)



(b)



(c)

Figure 11—Response of the *Festuca scabrella-F. idahoensis* habitat type to 300 passes per year. Before trampling (a), the combined cover of nine species was 135 percent. After 3 years of 300 passes per year (b) only four species were found, primarily because the forbs had withered by late summer; combined cover was still 85 percent. Three years after trampling ceased (c), eight species had a combined cover of 140 percent. *Festuca scabrella* contributed most of the cover at all observation periods. This illustrates the high resistance/high resilience response.

(a)

(b)

(c)

Figure 12—Response of the *Abies lasiocarpa/Xerophyllum tenax* habitat type to 300 passes per year. Before trampling (a), the combined cover of seven species was 155 percent. After 3 years of 300 passes per year (b), only *Xerophyllum tenax* survived (45 percent cover). Three years after trampling ceased (c), six species were present, but they had a combined cover of only 88 percent. Species composition was similar to that before trampling, however. This illustrates the moderately low resistance/low resilience response.

For species persistence, the relationship between trampling intensity and amount of recovery is more direct. Across the range of intensities used in these experiments, amount of recovery increased as trampling intensity increased. No threshold, beyond which increased trampling reduced recovery, was reached. It seems probable that such a threshold does exist; if so it would require much heavier trampling or more than 3 years of trampling.

Liddle (1975b) has advanced the hypothesis that there is a positive correlation between the number of passes required to reduce cover by 50 percent and primary productivity. When only the initial resistance of the vegetation is considered—as in Liddle's hypothesis—the data from this study contradict this notion. The most productive of the forested types, ABLA/CLUN (Pfister and others 1977), is the least resistant to trampling damage. Examination of the results of other trampling experiments that simply measured the initial loss of cover following trampling also reveals little relationship to productivity (Cole 1985). But if the hypothesis is modified to suggest a positive relationship between productivity and the ability to recover from trampling damage, then the data corroborate the hypothesis. ABLA/CLUN is the type that experienced the greatest amount of recovery. This is not surprising because productivity is usually estimated by measuring the difference in biomass between two harvest times.

INDIVIDUAL SPECIES RESPONSES

Deterioration

All species lost cover as trampling intensity increased, but there were pronounced differences in rate of loss. Some species were virtually eliminated after just 1 year of light trampling while others survived 3 years of heavy trampling. Figure 13 shows the response of five species that range from most to least resistant. *Thalictrum occidentale* (western meadowrue), a very sensitive species, was eliminated after 75 passes in just 1 year. *Linnaea borealis* (twinflower), a species that is neither particularly sensitive nor resistant, retained more than 50 percent cover after 3 years of 75 passes per year, but was nearly eliminated at a trampling intensity of 300 passes per year. *Festuca scabrella*, one of the most resistant species, retained more than 60 percent cover after 3 years of 300 passes per year, and more than 20 percent cover survived 3 years of 1,200 passes per year.

Differences in amount of loss resulting from successive years of trampling are also apparent. The most common response (for example, *Calamagrostis rubescens* [pinegrass] and *Linnaea borealis*), is for the first year to cause the most loss, for the second year to cause substantial additional loss, and for the third year to have little effect. For the most resistant species, such as *Festuca scabrella*, the third season of trampling often did cause substantial additional loss, particularly on the most heavily trampled lanes. Such species have a high initial resistance to cover loss, but severe trampling eventually causes pronounced losses. The least resistant species, such as *Thalictrum occidentale*, lose most cover after the first trampling season, and cover may actually increase after additional seasons of trampling, at least on lightly trampled lanes. Although such species have a very low tolerance for trampling, light trampling appears to elicit a response that increases their ability to survive further trampling. Although this type of response has not been reported elsewhere, several authors have reported increases in cover and biomass following low levels of trampling (Liddle 1975a).

Recovery

All species regained at least some lost cover during the 3-year period that followed the cessation of trampling. Most species also regained cover during the 10-month recovery periods that were interspersed with each trampling treatment. The resilience of species—their ability to increase in cover following trampling—varied greatly. Moreover, their ability to recover shortly after trampling ceased (for example, in the period between trampling

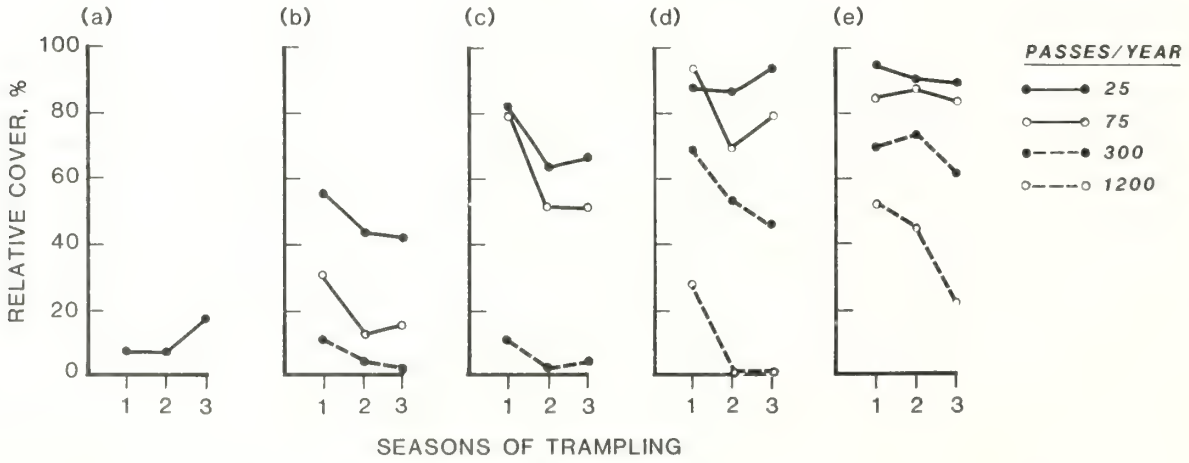


Figure 13—Loss of relative cover of (a) *Thalictrum occidentale*, (b) *Calamagrostis rubescens*, (c) *Linnaea borealis*, (d) mosses, and (e) *Festuca scabrella* over three seasons of trampling at various intensities. Relative cover, always 100 percent before treatment, is the proportion of the original cover still present after trampling, adjusted for changes on controls.

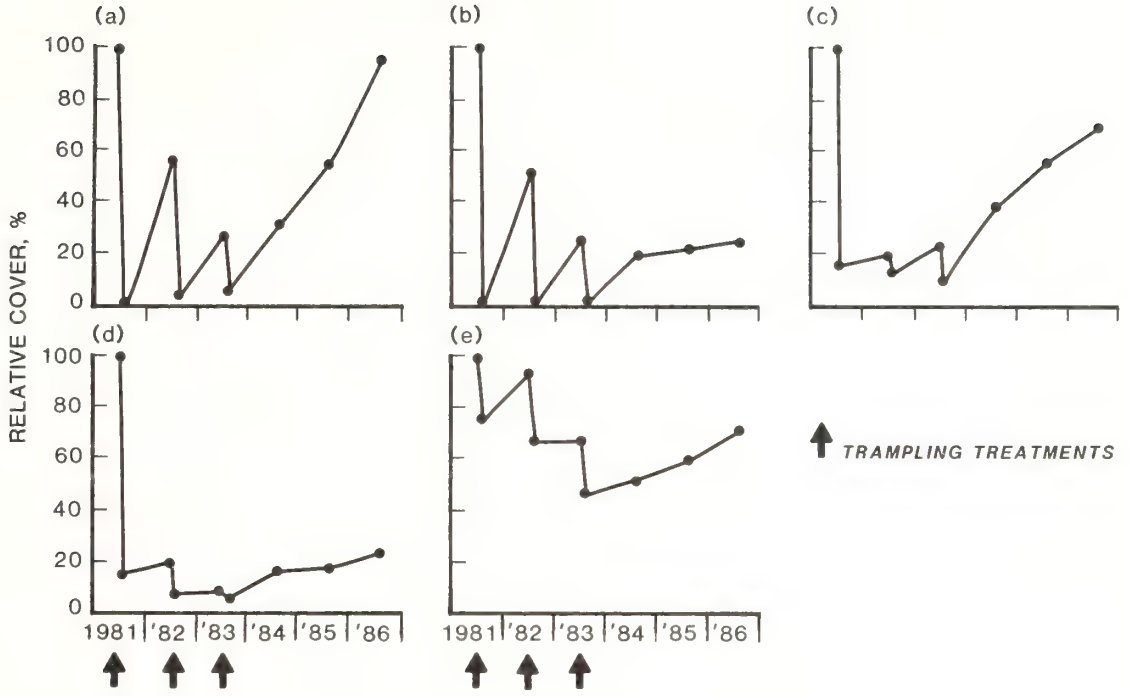


Figure 14—Deterioration and recovery of (a) *Arnica latifolia*, (b) *Thalictrum occidentale*, (c) *Berberis repens*, (d) *Fragaria virginiana*, and (e) *Xerophyllum tenax* following trampling at an intensity of 300 passes per year. Relative cover is the proportion of the original vegetation still present at some later date, adjusted for changes on controls.

seasons) was often different from their ability to recover over a longer period (for example, during the 3-year recovery period). Thus, it seems appropriate to distinguish between short- and long-term resilience.

Figure 14 shows five different responses. *Arnica latifolia* (mountain arnica) was virtually eliminated by 300 passes, but 10 months later it had regained over 50 percent of its original cover. This high short-term resilience diminished some after the second trampling season. But long-term recovery remained relatively high; cover 3 years after trampling ceased was 92 percent of original cover. *Thalictrum occidentale* also has high short-term resilience, but its long-term resilience is low. Successive years of trampling diminish its resilience substantially. *Berberis repens* (creeping Oregongrape) has low short-term resilience, but once trampling was eliminated for a long period of time, it recovered steadily. Long-term resilience is relatively high. *Fragaria virginiana* (blueleaf strawberry) is a species in which both short- and long-term resilience is low. The resilience of resistant species, such as *Xerophyllum tenax*, is more difficult to evaluate because they retain most of their cover except when severely trampled.

Classification of Species

With the exceptions of *Festuca scabrella* and *Xerophyllum tenax*, all species were nearly eliminated at some trampling intensity over the 3-year period. The lowest trampling intensity at which this occurred was used to categorize species according to resistance (table 6). My formal definition of "near-elimination" was a reduction in frequency of occurrence in subplots to 50 percent of pretrampling frequency and a reduction in relative species cover to 20 percent. If near-elimination occurred at trampling intensities of 40 passes per year or less, species were termed very sensitive; species that did not experience near-elimination except at intensities of 1,200 passes per year or more were termed very resistant. Intermediate terms and trampling intensities were sensitive (75 to 100 passes per year), neither resistant nor sensitive (200 to 400 passes per year), and resistant (600 to 900 passes per year).

Species were categorized according to resilience on the basis of how they recovered from moderate trampling. Short-term resilience was based on the increase in cover between the end of the first trampling season and the start of the second trampling season. Increase was the median difference in cover for the 200-, 300-, and 400-pass lanes between August 1981 and June 1982. If this median increase was greater than 30 percent, short-term resilience was high (table 6). Resilience was moderate if the increase was 10 to 30 percent and low if the increase was less than 10 percent. Fewer classes were used than for resistance because responses were more variable and, therefore, more difficult to categorize. Long-term resilience was classified in exactly the same manner, except that the measurements compared were those taken in August 1983 (immediately after three seasons of trampling) and in July 1986 (after 3 years of recovery).

This classification can be used to predict the response of these species to trampling disturbance. Habitat types with large proportions of resistant or resilient species are likely

Table 6—Classification of the more abundant species according to their resistance and resilience

Species	Resistance[1]	Resilience	
		Short-term	Long-term[3]
SHRUBS AND SUBSHRUBS			
Amelanchier alnifolia (western serviceberry)	M	L	M
Acrostaphylos uva-ursi (kinnikinnick)	M	L	L
Berberis repens (creeping Oregongrape)	M	L	M-H
Chimaphila umbellata (prince's-pine)	L	L	L
Linnaea borealis (twinflower)	M	L	H
Pachistima myrsinites (mountain-lover)	M	L	L-M
Rosa gymnocarpa (baldhip rose)	M	L-M	M
Rubus parviflorus (thimbleberry)	L	H	H
Spiraea betulifolia (shiny-leaf spirea)	L	M-H	M-H
Symphoricarpos albus (snowberry)	L	M-H	H
Vaccinium caespitosum (dwarf huckleberry)	M	M	-
Vaccinium globulare (globe huckleberry)	L	L	M
Vaccinium scoparium (grouse whortleberrry)	M	L	M
GRAMINOIDS			
Calamagrostis rubescens (pinegrass)	L	L-M	L
Carex concinnoides (northwest sedge)	M	L	L
Carex geyeri (elk sedge)	H	L	M
Festuca scabrella (rough fescue)*	VH	L	M
FORBS			
Achillea millefolium (common yarrow)	M	M	M
Adenocaulon bicolor (pathfinder)	VL	H	H
Antennaria racemosa (raceme pussy-toes)	M	L	L
Arenaria congesta (capitate sandwort)*	VH	M	M
Arnica cordifolia/A. latifolia (heart-leaf/mountain arnica)	L	H	H
Aster conspicuus (showy aster)	VL	H	H
Aster foliaceus (leafy aster)	L	L	H
Chrysopsis villosa (hairy golden-aster)	H	M	M
Clintonia uniflora (queen's cup beadlily)	L	H	M
Epilobium angustifolium (fireweed)	VL	H	H
Eriogonum umbellatum (sulfurflower)	M	L	M
Fragaria virginiana (blueleaf strawberry)	L	L-M	L-M
Galium triflorum (fragrant bedstraw)	L	L	H
Geranium viscosissimum (sticky purple geranium)	L	H	H
Goodyera oblongifolia (western rattlesnake-plantain)	M	L	L
Hedysarum occidentale (western sweetvetch)	VL	H	-
Hieracium albiflorum (white flowered hawkweed)	M	L	L
Lupinus argenteus (silvery-lupine)	VL	M	-
Lupinus sericeus (silky lupine)	VL	H	H
Melampyrum lineare (narrow-leaved cow-wheat)	VL	H	H
Osmorhiza chilensis (mountain sweet-root)	L	H	H
Penstemon confertus/P. procerus (yellow/small-flowered beardtongue)	M	H	M
Potentilla gracilis (slender cinquefoil)	M	H	H
Smilacina stellata (starry false Solomon's seal)	L	H	M
Solidago missouriensis (Missouri goldenrod)	H	M	M
Thalictrum occidentale (western meadowrue)	VL	H	M
Viola orbiculata (round-leaved violet)	M	M	M
Xerophyllum tenax (beargrass)*	VH	L	M
TREE SEEDLINGS	L	L	L
MOSSES*	H	L-M	M
LICHENS	L	M	L

[1]Resistance was based on the number of passes per year required to reduce frequency of occurrence in subplots to 50 percent of pretrampling frequency and relative cover to 20 percent. Classes are: very high (VH) (≥1,200 passes per year); high (H) (600-900 passes per year); moderate (M) (200-400 passes per year); low (L) (75-100 passes per year); very low (VL) (≤40 passes per year).

[2]Short-term resilience was based on the increase in relative cover between the end of the first trampling season (August 1982) and the start of the second trampling season (June 1982). The median increase on the 200-, 300-, and 400-pass lanes was used as an indicator of recovery following moderate trampling. Classes are: high (H) (>30 percent increase); moderate (M) (10-30 percent increase); low (L) (<10 percent increase).

[3]Long-term resilience was based on the increase in relative cover between the end of the last trampling season (August 1983) and the end of the recovery period 3 years later (July 1986). The median of the 200-, 300-, and 400-pass lanes was used. The response of species with an asterisk (*) was evaluated on more heavily trampled lanes so that response following severe cover loss could be evaluated.

to tolerate trampling well or recover quickly from trampling damage. Generally, we can predict that intermittent light trampling will be least damaging where species are resistant. Intermittent heavy trampling will be least damaging where species have high short-term resilience; prolonged trampling, particularly if it is heavy, will be least damaging where long-term resistance is high. A more definitive picture of how species respond to different intensities and frequencies of disturbance can be gained by integrating resistance and resilience.

Integration of Resistance and Resilience

For the 18 most widely distributed species, it is possible to integrate both resistance and long-term resilience using the modification of Bayfield's (1979) ordination (fig. 15). This illustrates the ability of each species to resist and recover from the impact of being trampled 300 times per year for 3 years. Three clusters of response are obvious. In the lower right corner of the graph are sensitive species with low resilience: *Chimaphila umbellata* (prince's-pine), *Vaccinium globulare* (globe huckleberry), *Calamagrostis rubescens, Thalictrum occidentale, Smilacina stellata* (starry false Solomon's seal), *Vaccinium scoparium* (grouse whortleberry), and lichens. In the upper right corner are species of intermediate resistance and high resilience: *Linnaea borealis*, *Arnica cordifolia* (heart-leaf arnica), *Spiraea betulifolia* (shiny-leaf spirea), *Berberis repens*, and *Achillea millefolium* (common yarrow). Resistant species that do not recover much—in the upper left and center of the graph—are *Arenaria congesta* (capitate sandwort),

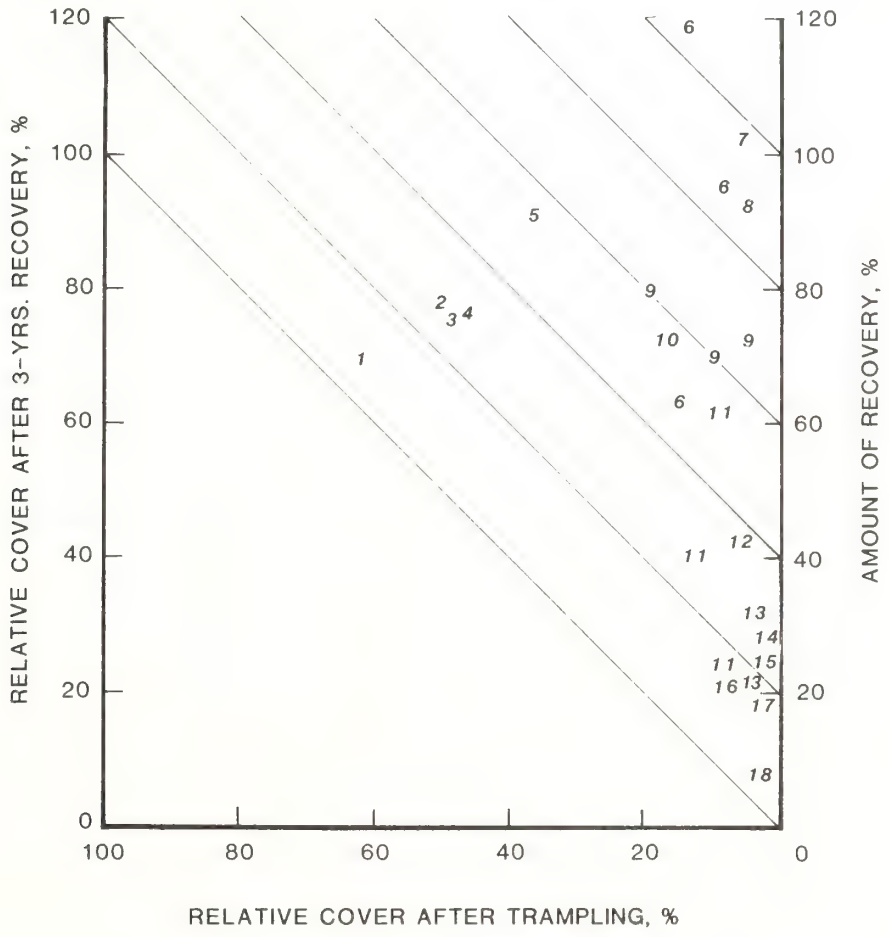


Figure 15—Cover loss and recovery of common species following moderate trampling (300 passes per year for 3 years). Relative cover is the proportion of original cover present, adjusted for changes on controls. Amount of recovery, the diagonal lines with values along the right axis, is the increase in cover that occurred during the 3 years following the cessation of trampling. Species are: (1) *Festuca scabrella*, (2) *Arenaria congesta*, (3) *Xerophyllum tenax*, (4) mosses, (5) *Solidago missouriensis*, (6) *Spiraea betulifolia*, (7) *Linnaea borealis*, (8) *Arnica cordifolia*, (9) *Berberis repens*, (10) *Achillea millefolium*, (11) *Fragaria virginiana*, (12) *Vaccinium scoparium*, (13) *Calamagrostis rubescens*, (14) *Smilacina stellata*, (15) *Thalictrum occidentale*, (16) lichens, (17) *Vaccinium globulare*, and (18) *Chimaphila umbellata*.

Festuca scabrella, *Xerophyllum tenax*, and mosses. The response of these species following the cessation of heavy trampling indicates that *Festuca scabrella* and *Arenaria congesta* are quite resilient, while the resilience of *Xerophyllum tenax* and mosses is less. *Solidago missouriensis* (Missouri goldenrod) is moderately resistant and resilient.

Three species were abundant in several different habitat types. In each of three habitat types, *Berberis repens* was neither resistant nor sensitive (5 to 20 percent cover survived 300 passes per year); resilience was moderately high in each type (cover increased 60 to 70 percent after trampling ceased). The resistance of *Spiraea betulifolia* was also similar in each of three habitat types (8 to 15 percent survival). Resilience, however, was much higher in the ABLA/CLUN type (cover increased more than 100 percent) and in PSME/SYAL (85 percent increase) than in ABLA/XETE (50 percent increase). The resistance of *Fragaria virginiana* was also similar in three types (7 to 12 percent survival), while resilience varied greatly. Again, resilience was greatest in ABLA/CLUN (50 percent increase) and less in ABLA/CLUN-VACA (30 percent increase) and PSME/SYAL (20 percent increase). These results indicate that resilience can vary greatly within the same species while resistance does not. This corroborates the hypothesis that resistance is determined primarily by plant characteristics, while resilience is strongly influenced by habitat factors such as soil fertility, moisture regime, and length of the growing season (Cole 1987b).

Figure 16 provides examples of four basic types of response: low resistance and resilience (lichens), low resistance and high resilience (*Arnica cordifolia*), high resistance and low resilience (*Xerophyllum tenax*), and high resistance and resilience (*Arenaria congesta*). Differences in resistance among these species are greatest at moderate trampling intensities of 200 to 800 passes per year. Differences in resilience are most pronounced at the highest intensities.

Resistance and resilience are also integrated in the concept of **recovery level**. Recovery level, as defined earlier, is a measure of cover following both a period of deterioration and a period of recovery. Recovery level can be high for resistant species with low resilience, such as *Xerophyllum tenax*, and sensitive species with high resilience, such as *Arnica cordifolia*, as well as for resistant and resilient species, such as *Arenaria congesta* (fig. 16). In fact, many of the species with the highest relative cover 3 years after trampling ceased were sensitive species that were eliminated by moderate and heavy trampling.

Of particular interest is the level of trampling each species can endure and still recover to a condition close to

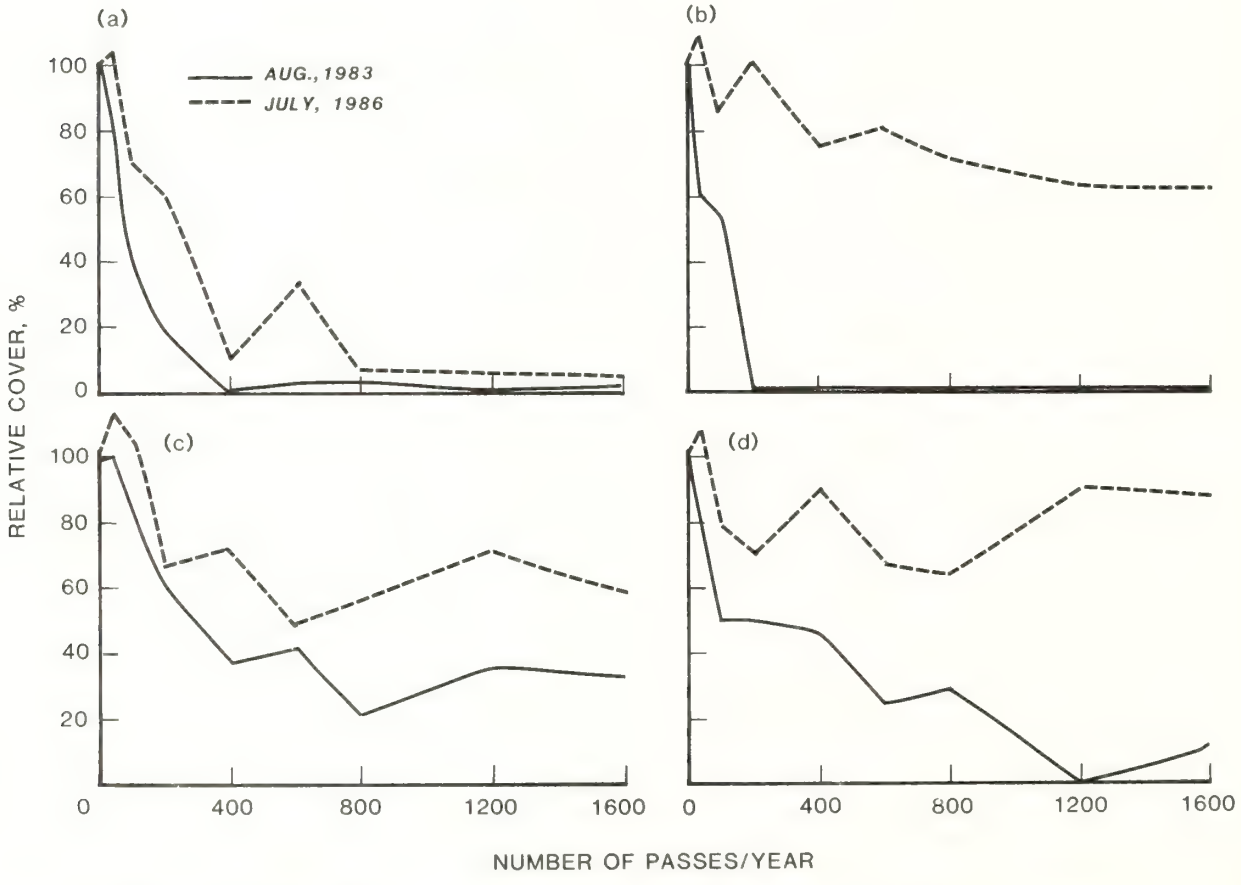


Figure 16—Relationship between trampling intensity and relative cover after three seasons of trampling (August 1983) and 3 years of recovery (July 1986) for (a) lichens, (b) *Arnica cordifolia*, (c) *Xerophyllum tenax*, and (d) *Arenaria congesta*. Relative cover is the proportion of original cover present, adjusted for changes on controls.

what existed prior to trampling. Using relative cover of at least 80 percent as a definition of near-complete recovery, the maximum number of passes per year each species tolerated and still nearly recovered was determined. Both short-term recovery—between August 1981 and June 1982 (after one season of trampling and 10 months of recovery)—and long-term recovery—between August 1983 and July 1986 (after 3 years of trampling and 3 years of recovery)—were evaluated (table 7).

Managers can use this table when attempting to control use levels such that these species are not permanently damaged. The column for short-term recovery is most appropriate when considering the effects of intermittent trampling, such as cross-country hiking or highly dispersed camping in areas without well-developed campsites. Long-term recovery is most appropriate for considering how species are likely to recover after a period of prolonged use.

What Determines Amount of Deterioration and Recovery?

Amount of deterioration was strongly influenced by trampling intensity. All species declined in cover as trampling intensity increased. Habitat type had little influence on loss of cover, however. Those species that were found in several different types tended to experience similar losses in each type.

This finding runs counter to the conclusion of some researchers that the resistance of species is strongly influenced by environmental factors such as soil conditions, topography, and other vegetation on the site (Kuss and Graefe 1985; Price 1985). Some of this discrepancy might be explained by the tendency to confuse species resistance with habitat resistance. Wet soils, for example, are more seriously compacted by trampling than drier soils, and the species that occupy such sites are usually more susceptible than those that occupy dry sites (Strand 1979; Willard and Marr 1970). But they usually are very different species. We have very little data to evaluate whether an individual species is more sensitive to trampling when growing in wet or dry soils.

One experimental study that did provide some data on the response of the same species in different environments was Holmes and Dobson's (1976) study of subalpine meadows in Yosemite National Park. They found that resistance tended to be low in pure communities as opposed to mixed communities, in dry and sandy soils, and on steeply sloping sites. Apparently layered communities offer more protection to plants. Tall plants can shelter smaller plants and ground-level plants cushion taller plants when they are pressed against the ground surface. Also, dry and sandy soils can be easily gouged and displaced by boots, either burying or uprooting plants. Displacement is aggravated on steeper slopes. Even these generalizations were based on the responses of only a few species in an unreplicated experiment.

In the study reported here, it was obvious that the persistence of resistant clumps of *Festuca scabrella* protected many of the other species growing in that habitat type. In some cases only underground plant parts were protected; this is reflected in the trampling intensities species can tolerate and still recover (table 7). For example, two morphologically similar species, *Lupinus argenteus* (silvery lupine), which was on the ABLA/VACA plots, and *Lupinus sericeus* (silky lupine), which was on the FESC-FEID plots, were eliminated by low levels of trampling. In neither case were the aerial parts of the plants protected from damage. But *L. argenteus* could recover only from light trampling, while *L. sericeus* recovered from very heavy trampling. A likely explanation for this result is that the remnant *Festuca scabrella* clumps absorb much of the trampling impact and protect the underground perennating organs of *L. sericeus*. In the absence of *Festuca scabrella* clumps, perhaps *Lupinus sericeus* would have been so damaged by heavy trampling that it too would not have recovered.

The aerial parts of low-growing plants may also be protected from trampling damage. Three highly resistant species on the FESC-FEID plots, *Arenaria congesta*, *Chrysopsis villosa* (hairy golden-aster), and *Solidago missouriensis*, have characteristics that make them resistant to trampling (these will be discussed in more detail later). But their survival rates would probably have been much lower if they were unable to grow underneath persistent grass clumps. In fact, their survival rates were often considerably reduced on subplots that did not have much *Festuca scabrella* cover.

It was also obvious that wherever the microtopography was hummocky, trampling was concentrated on the tops of hummocks and plants that grew there were particularly vulnerable, while those growing in depressions were largely spared. Often such differences in microtopography are reflected in differences in species composition. In Olympic National Park, for example, Bell and Bliss (1973) report more damage to *Lupinus lepidus* (prairie lupine), which grows on the tops of hummocks, than to *Carex phaeocephala* (dunhead sedge), which grows on hummock sides. In this case, topography makes it more likely that *L. lepidus* will be damaged than *C. phaeocephala* because hummocks are more likely to be trampled and *L. lepidus* is more likely to grow on hummocks. But the hummocks do not alter the inherent resistance of these two species to trampling.

In sum, we have insufficient data to make generalizations about the importance of habitat factors in modifying the resistance of individual species; statements to the contrary should be treated as working hypotheses. In this study, habitat differences had little effect. There are theoretical grounds for believing that substantial differences in environmental factors, such as light intensity or soil moisture, might affect the resistance of a given plant species to trampling. But where such differences exist, they are usually reflected in dramatic differences in species composition. While environmental factors may exert some influence on the resistance of individual species—further research might allow us to quantify this better—their primary influence on resistance is probably indirect. By profoundly influencing the relative importance of individual species, each with its own inherent resistance, environmental factors exert considerable control on the resistance of the entire community. This is reflected in differences in the resistance of each habitat type.

Table 7—Trampling intensities species can tolerate and still recover[1]

Species	Recovery period	
	Short-term	Long-term
SHRUBS AND SUBSHRUBS		
Arctostaphylos uva-ursi (kinnikinnick)	VL-L	L
Berberis repens (creeping Oregongrape)	VL-L	H
Chimaphila umbellata (prince's-pine)	L	VL
Linnaea borealis (twinflower)	VL-L	M-VH
Pachistima myrsinites (mountain-lover)	VL-L	VL-L
Spiraea betulifolia (shiny-leaf spirea)	VL-L	M-VH
Symphoricarpos albus (snowberry)	VL	M-VH
Vaccinium caespitosum (dwarf huckleberry)	VL	-
Vaccinium globulare (globe huckleberry)	VL	VL
Vaccinium scoparium (grouse whortleberry)	VL	L
GRAMINOIDS		
Calamagrostis rubescens (pinegrass)	VL-L	VL-L
Carex concinnoides (northwest sedge)	L	VL
Festuca scabrella (rough fescue)	M	M
FORBS		
Achillea millefolium (common yarrow)	VH	H
Adenocaulon bicolor (pathfinder)	L	H
Antennaria racemosa (raceme pussy-toes)	VL	L
Arenaria congesta (capitate sandwort)	M	VH
Arnica cordifolia/A. latifolia (heart-leaf/mountain arnica)	M-H	H
Aster conspicuus (showy aster)	L	L-H
Chrysopsis villosa (hairy golden-aster)	H	M
Clintonia uniflora (queen's cup beadlily)	L	H
Fragaria virginiana (blueleaf strawberry)	VL-L	L
Galium triflorum (fragrant bedstraw)	VL	VH
Geranium viscosissimum (sticky purple geranium)	M	VH
Goodyera oblongifolia (western rattlesnake-plantain)	L	L
Hedysarum occidentale (western sweetvetch)	L	-
Hieracium albiflorum (white-flowered hawkweed)	L	L
Lupinus argenteus (silvery lupine)	L	-
Lupinus sericeus (silky lupine)	VH	VH
Melampyrum lineare (narrow-leaved cow-wheat)	L	M
Osmorhiza chilensis (mountain sweet-root)	L	M-H
Potentilla gracilis (slender cinquefoil)	H	VH
Smilacina stellata (starry false Solomon's seal)	L	L
Solidago missouriensis (Missouri goldenrod)	H	VH
Thalictrum occidentale (western meadowrue)	L	VL-L
Viola orbiculata (round-leaved violet)	L	M
Xerophyllum tenax (beargrass)	M-H	L
TREE SEEDLINGS	VL	VL
MOSSES	L-M	H
LICHENS	L	VL

[1]Species were evaluated on the basis of the maximum number of passes per year for lanes on which relative cover was at least 80 percent either (a) after one season of trampling and one 10-month recovery period (short-term) or (b) after three seasons of trampling and 3 years of recovery (long-term). Classes of trampling intensity were very heavy (VH) (≥1,200 passes); heavy (H) (600-900 passes); moderate (M) (200-400 passes); light (L) (75-100 passes); very light (VL) (≤40 passes).

The primary factor influencing the damage caused by a given level of trampling appeared to be the morphological characteristics of each species. While all species declined in cover as trampling intensity increased, some declined much more than others. The ability of a species to avoid being damaged by trampling appeared to be most strongly related to characteristics of the aerial portion of the plant. This has been noted before by Schreiner (1973) and Rees and Tivy (1978), despite the former's attempt to relate resistance to location of the perennating bud. Location of buds is likely to affect resilience and even the ability to survive repeated trampling, but there is little reason to expect it to affect the ability to survive one season of trampling.

The characteristics that have the greatest influence on resistance appear to be the woodiness, flexibility, erectness, height, and density of stems, and the location, size, and strength of leaves. Most woody shrubs and subshrubs are moderately resistant (table 6). The more resistant of these are large (such as *Amelanchier alnifolia*), have stout stems and branches (such as *Berberis repens*), or have flexible stems that creep along the ground (such as *Arctostaphylos uva-ursi* [kinnikinnick]). Woody species that are erect, with stems and branches that are not stout (such as *Spiraea betulifolia*) or are brittle (such as *Vaccinium globulare*) are more sensitive. Woodiness precludes a species from being resistant, but it gives the plant enough strength so that it is not likely to be highly sensitive.

Responses of herbaceous species are more divergent. All of the species with high and very high resistance had densely clustered stems and/or basal leaves that form resistant and persistent mats or tufts. These include both dicotyledonous species with flexible stems projecting from a woody caudex and monocotyledonous species with dense clusters of basal leaves. The very most resistant of these also have leaves that are tough and either small (such as *Arenaria congesta*) or long and thin (such as *Festuca scabrella* and *Xerophyllum tenax*). All of the herbs that did not grow in dense clusters were quite sensitive to trampling. For these species, sensitivity increased with increasing plant height and leaf/stem ratio.

As has been reported in most other studies, mosses were quite resistant to at least moderate levels of trampling while lichens were quite sensitive; neither exhibited an extreme response. The resistance of mosses was particularly pronounced where they formed a thick mat. This mat was compressed by trampling but it acted as a springy cushion that absorbed much of the trampling pressure. A thin layer of mosses growing on rock would probably have been more easily abraded and been much more sensitive. Lichens tended to break rather than compress and, therefore, were readily damaged by trampling.

In contrast to resistance, the resilience of individual species **did** differ between habitat types; this suggests that resilience is influenced substantially by environmental factors. Plants growing on the ABLA/CLUN plots, in particular, recovered much more than individuals of the same species on other habitat types. The cause of this greater resilience was not determined, but ABLA/CLUN is generally the most productive of the forested types (Pfister and others 1977). Soil fertility and moisture and a long growing season could also have contributed.

Although environmental factors strongly influence resilience, characteristics of the plants themselves remain important as well. Position of the perennating bud and physiological characteristics such as reproductive capacity and growth rates become extremely important. Short-term resilience is low in most of the shrubs (table 6) that have perennating buds above the ground surface where they can be injured by trampling. Shrubs that can sprout vigorously from rhizomes (such as *Spiraea betulifolia* and *Symphoricarpos albus*) can grow back quickly, however. Given a reprieve from trampling, most shrubs grow slowly but steadily.

The most resilient species are herbaceous ones that die back every winter to perennating buds located at or beneath the ground surface. Growth can be either from a rhizome (such as *Arnica cordifolia*) or a caudex (such as *Osmorhiza chilensis*). Growth tended to be less in species with aerial parts that persist from year to year (such as *Festuca scabrella* and *Xerophyllum tenax*) and species with perennating organs that were not tough enough to survive heavy trampling (such as *Calamagrostis rubescens*). Several rhizomatous species were highly resilient after the first trampling dosage (fig. 17), but successive years of trampling diminished this resilience (for example, *Clintonia uniflora*, *Smilacina stellata*, and *Thalictrum occidentale*). Either the rhizomes were increasingly injured after each year, or loss of photosynthetic tissues every year eventually diminished carbohydrate reserves to the point where resprouting could not occur. The one widespread annual on these plots, *Melampyrum lineare* (narrow-leaved cow-wheat), proved to be highly resilient, having little problem reproducing by seed even on quite severely trampled lanes.

One interesting conclusion is that few species were both highly resistant and resilient; similarly, few have both low resistance and resilience. The species that can resist trampling are those with tough aerial parts that develop over several growing seasons. Once destroyed, it takes several years for these parts to grow back. The species that can grow rapidly enough to cover a trampled site tend to have aerial parts that are flimsy and spreading and, therefore, unable to resist trampling.

In sum, shrubs generally had moderate resistance, low short-term resilience, and variable long-term resilience. Several of the less resistant shrubs were quite resilient. Graminoids varied greatly in resistance and long-term resilience; all had low short-term resilience. The more resistant species were also most resilient. Forbs were also variable in response. The most common response is to have low resistance and high resilience. Several species had high short-term resilience but low long-term resilience, and several of the more resistant species were not highly resilient. Tree seedlings were not very resistant and they had low resilience; once irreparably damaged they must reproduce from seed. Mosses were quite resistant and moderately resilient, while lichens were neither resistant nor resilient.

(a)

(b)

(c)

Figure 17—A subplot in lane with 200 passes per year of the *Abies lasiocarpa/Clintonia uniflora* habitat type in (a) August 1981 (after the first season of trampling), (b) June 1982 (after the first overwinter recovery period), (c) August 1983 (after the third season of trampling), and (d) June 1984 (after the third overwinter recovery period). Species cover was 22 percent after the first trampling season (a) and only 7 percent after the third (c). Species cover was 91 percent after the first recovery period (b) and 57 percent after the third (d). *Berberis repens* provided a constant 15-percent cover, except immediately after the third season of trampling (c). *Thalictrum occidentale*, the dominant before trampling, recovered from the first season of trampling (35 percent cover in b), but not from the third (1 percent cover in d).

(d)

Fig. 17 (Con.)

RESPONSES OF SOIL ORGANIC HORIZONS

Deterioration

Response of the soil organic horizon was examined by measuring increases in exposed mineral soil that occurred when overlying organic horizons were removed by trampling and erosion. By August 1983, three successive summers of trampling had exposed mineral soil in all but one of the habitat types, ABLA/CLUN (table 8). Exposure increased as trampling intensity increased; however, in contrast to vegetation loss, the relationship between exposure and trampling intensity was linear (fig. 18). Compared to vegetation loss, much higher trampling intensities are required to expose a substantial amount of mineral soil.

Large standard errors in figure 18 indicate high variability. Some of this is local variability between subplots in the same habitat type, but much of it reflects large differences among types. Differences among types are most pronounced at the highest trampling intensities (another contrast to the response of vegetation).

A final contrast to vegetational response is provided by the response of exposure to successive years of trampling. Exposure increased after each successive year of trampling (fig. 19), particularly on the lanes that received the heaviest trampling; vegetation was generally not affected further by the third season of trampling. Loss of organic horizons and exposure of mineral soil is an impact that may worsen with continued trampling, without reaching an equilibrium level (at least within 3 years).

Recovery

Mineral soil exposure decreased rapidly after trampling was curtailed. Even the lanes trampled 1,600 times per year had a mean exposure of less than 1 percent after 3 years without trampling (table 9). Only the lane with 900 passes per year in ABLA/XETE had more than 3 percent exposure 3 years after trampling ceased.

Recovery was rapid on all habitat types (fig. 20). In the three forested types that experienced the least exposure following trampling, ABLA/CLUN, ABLA/CLUN-VACA, and PSME/SYAL, organic horizons covered the entire soil surface. ABLA/XETE, the type that experienced the most exposure, had recovered greatly, but some mineral soil was exposed on the most heavily trampled lanes. The FESC-FEID grassland, however, recovered more slowly. Median exposure on the most heavily trampled lanes was still 2.5 percent after 3 years of recovery. Even here, however, recovery of a complete litter cover should require only about 5 years.

Table 8—Increase[1] in mineral soil exposure after three seasons of trampling

Number of passes per year	Habitat type						All habitat types
	ABLA/ XETE	PSME/ SYAL	FESC- FEID	ABLA/ CLUN-VACA	ABLA/ VACA	ABLA/ CLUN	
	Percent						
0	0	0	0	0	0	0	0
5	0	0	+	0	0	0	+
15	0	0	0	0	0	0	0
25	0	0	1	0	0	0	+
40	0	0	0	0	0	0	0
75	2	2	1	0	0	0	1
80	1	3	1	0	0	0	1
100	3	1	1	0	+	0	1
200	2	1	+	1	1	0	1
300	7[b]	3[ab]	1[a]	+[a]	1[a]	0[a]	2
400	6	2	+	3	2	0	2
600	9	10	2	1	1	0	4
800	8	6	3	1	1	0	4
900	16	7	6	4	3	0	7
1,200	11[ab]	14[ab]	11[ab]	26[b]	2[a]	0[a]	10
1,600	22	11	17	8	2	0	11
Mean of all treatments	5	4	3	3	1	0	3

[1]Increase is the difference in percentage of mineral soil exposed before and after trampling. Any two values in the same row followed by the same letter are not significantly different (Duncan's multiple range test, $p = 0.05$). Rows with no letters have no significant differences. + indicates <0.5 percent exposure.

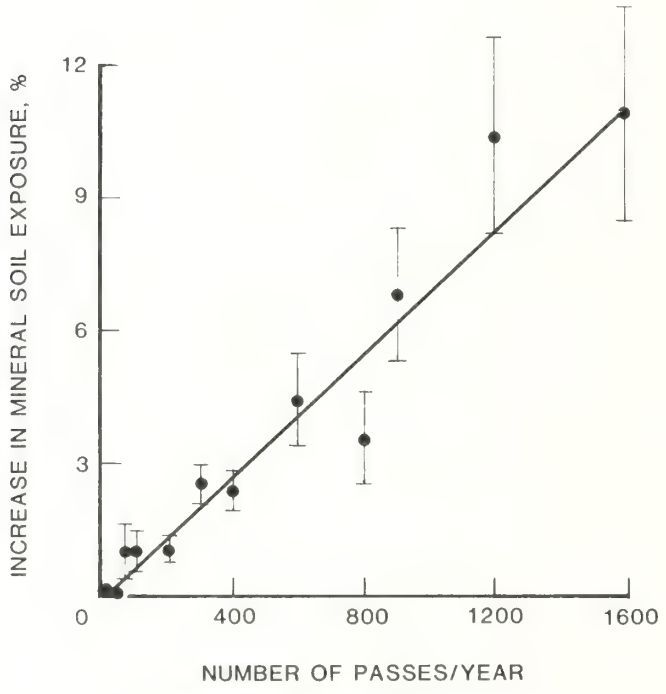


Figure 18—Relationship between trampling intensity and increase in mineral soil exposure after three seasons of trampling. Increase is the difference in percent mineral soil exposure before and after trampling. Data are the mean of all habitat types. Vertical bars are ±1 standard error.

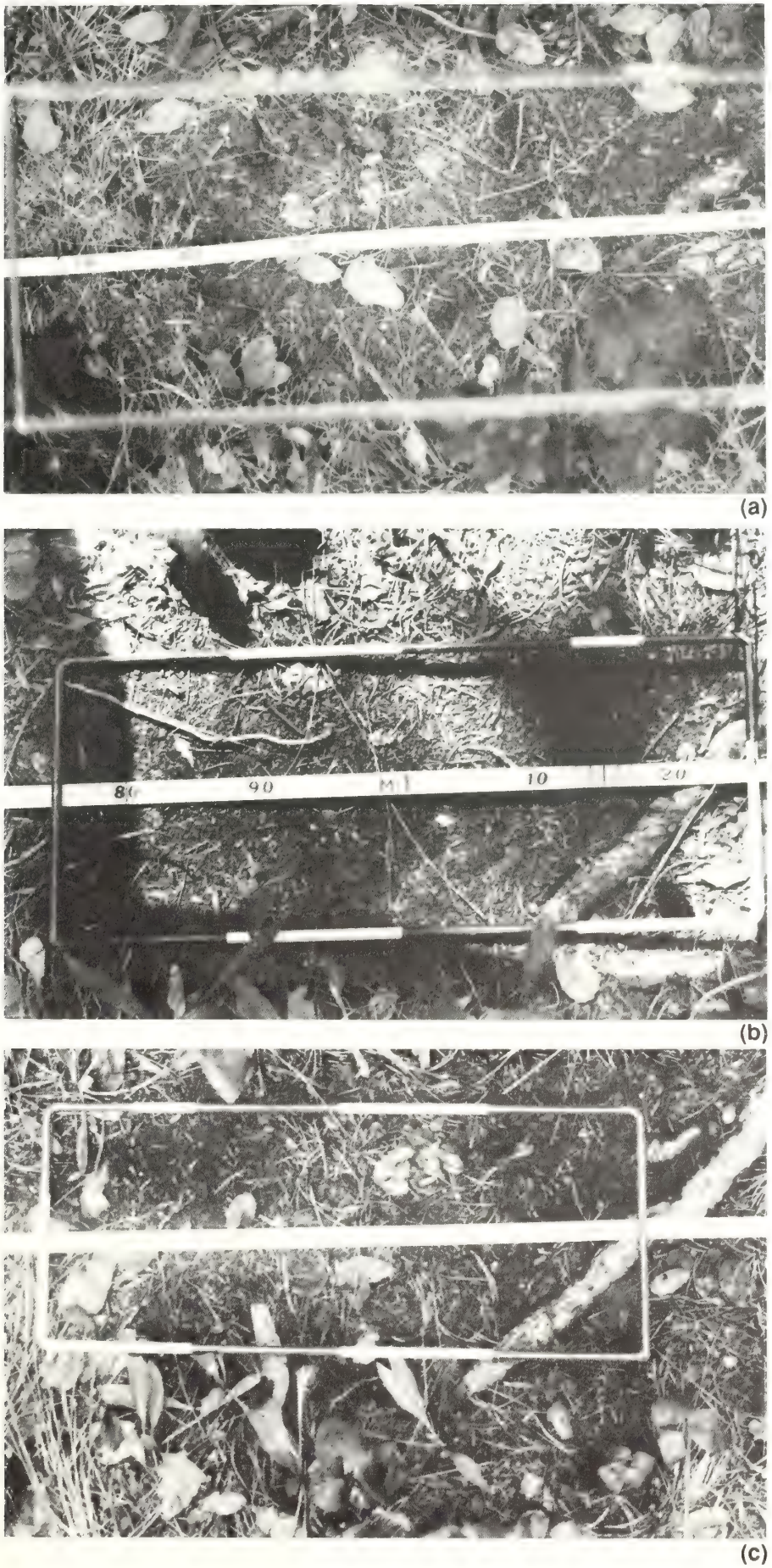


Figure 19—Progressive erosion of organic material and exposure of mineral soil on a subplot receiving 600 passes per year in the *Pseudotsuga menziesii/ Symphoricarpos albus* habitat type after one (a), two (b), and three (c) seasons of trampling.

Table 9—Increase[1] in mineral soil exposure 3 years after trampling ceased

Number of passes per year	Habitat type					All habitat types
	ABLA/ XETE	FESC- FEID	PSME/ SYAL	ABLA/ CLUN-VACA	ABLA/ CLUN	
	Percent					
0	0	0	0	0	0	0
5	0	0	0	0	0	0
15	0	0	0	0	0	0
25	0	0	0	0	0	0
40	0	0	0	0	0	0
75	+	+	0	0	0	+
80	+	0	0	0	0	0
100	0	0	0	0	0	0
200	1	0	0	0	0	+
300	0	0	0	0	0	0
400	1	0	0	0	0	+
600	1	0	+	0	0	+
800	1	1	1	0	0	1
900	5	1	0	0	0	1
1,200	+	3	+	1	0	1
1,600	1	3	0	0	0	1
Mean of all treatments	0.6	0.4	0.1	0.1	0	0.3

[1]Increase is the difference in percentage of mineral soil exposed before trampling and after trampling and recovery. No differences among habitat types were statistically significant (Duncan's multiple range test, $p = 0.05$). + indicates <0.5 percent exposure.

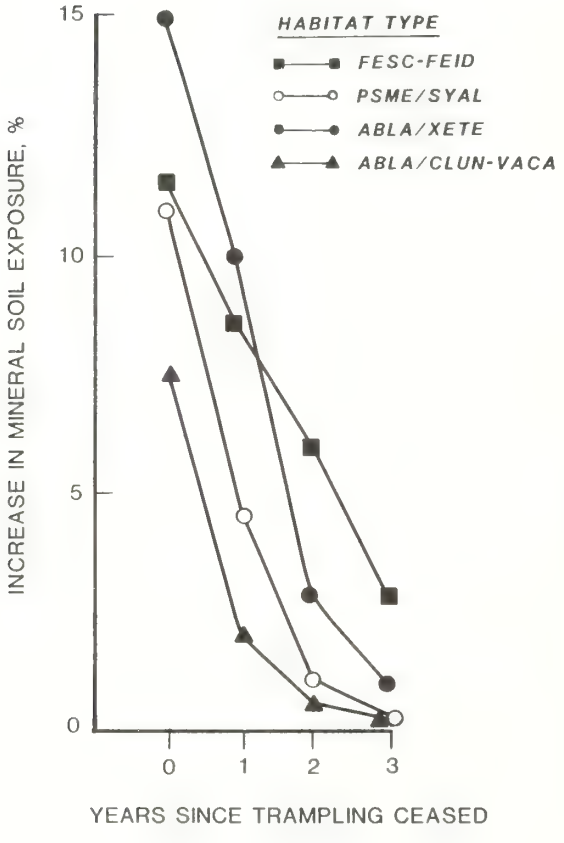


Figure 20—Differences among habitat types in recovery of organic horizons following the cessation of trampling. Increase in mineral soil exposure is the difference in percentage of mineral soil exposed before trampling and at some later date. Data are for heavy trampling intensities (median of 900, 1,200, and 1,600 passes per year). ABLA/CLUN had no soil exposure. Standard error ranges were 2.1 to 6.0 percent (year 0), 2.5 to 3.9 percent (year 1), 0.7 to 3.2 percent (year 2), and 0 to 1.8 percent (year 3).

The reader should note that the definition of recovery is two-dimensional, based entirely on surficial cover. Organic horizon depth was not measured, so it is not possible to draw any conclusions about loss or recovery of volume, weight, or depth of organic matter. It seems intuitively obvious that a reduction in depth and volume would occur more rapidly than an increase in area of mineral soil—much as species cover decreased more rapidly than vegetation cover. For example, the thick organic horizons on the ABLA/CLUN type were entrenched on the heavily trampled lanes, despite the lack of mineral soil exposure. It also seems obvious that recovery of the original depth and volume of organic matter would require a longer period of time than recovery of a complete surficial cover. Although exposure of mineral soil occurs more slowly than loss of vegetation and recovery occurs more rapidly, this does not necessarily mean that impact to organic horizons occurs more slowly and recovery is more rapid.

What Determines Amount of Deterioration and Recovery?

Both of the controlled variables, trampling intensity and habitat type, had a profound influence on amount of deterioration. Maximum exposure occurred on habitat types that had thin organic horizons initially or that were located on sloping sites. ABLA/CLUN had a mean organic horizon thickness of more than 4 inches (11 cm) and never experienced any soil exposure. ABLA/XETE, which experienced the most pronounced exposure, had a mean organic horizon thickness of only 0.25 inch (0.7 cm). PSME/SYAL experienced high exposure, despite having organic horizons that averaged more than 2 inches (6 cm) in depth. These plots were located on a 20 to 25 percent slope, however; this promoted downslope movement of material disturbed by trampling (despite the fact that lanes paralleled contours).

There was a linear relationship between mineral soil exposure and trampling intensity on all habitat types. On ABLA/CLUN no exposure occurred on any lane. In the other types the linear relationship was positive, with the slope of regression lines increasing from the more-resistant types (ABLA/VACA and ABLA/CLUN-VACA) to the less-resistant types (ABLA/XETE and PSME/SYAL).

Amount of recovery (decrease in mineral soil exposure) is most strongly influenced by trampling intensity (fig. 21). The rate and amount of recovery increases as trampling intensity increases. Those sites that experienced the most exposure also recovered the most. Litter fall on all of these habitat types is sufficient to cover the entire ground surface, regardless of exposure level, within 3 to 5 years.

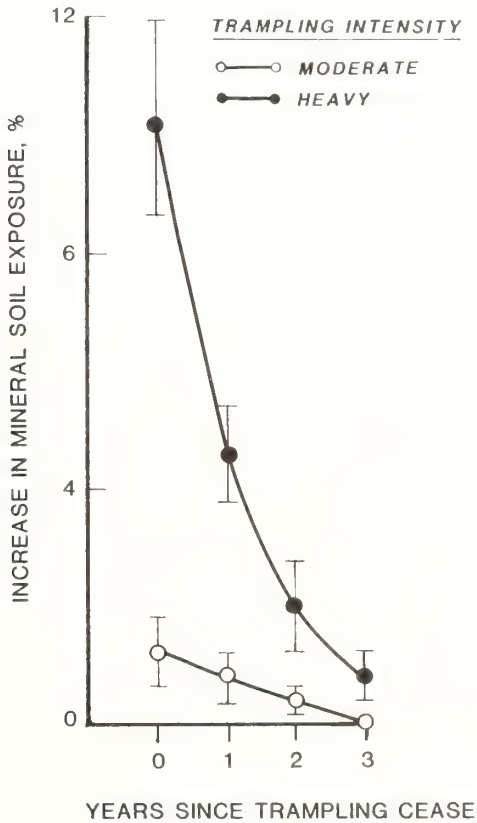


Figure 21—Recovery of organic soil horizons following cessation of heavy trampling (median of 900, 1,200, and 1,600 passes per year) and moderate trampling (median of 100, 200, and 300 passes per year). Increase in mineral soil exposure is the difference in percentage of mineral soil exposed before trampling and at some later date. Data are the mean of all habitat types. Vertical bars are ±1 standard error.

COMPACTION AND RECOVERY OF THE MINERAL SOIL

Deterioration

By August 1983, three successive summers of trampling had compacted the mineral soil, increasing the soil's resistance to penetration. Penetration resistance increased as trampling intensity increased (table 10). The relationship between trampling intensity and increase in penetration resistance was asymptotic rather than linear (fig. 22). The second season of trampling resulted in higher levels of compaction than the first season, but the third trampling season had no additional effect. In regards to the nature of the relationship to trampling intensity and the effects of successive trampling seasons, the response of penetration resistance is more similar to that of vegetation cover than of exposure of mineral soil.

Differences among habitat types in the severity of compaction were pronounced, particularly at trampling intensities of 400 to 900 passes per year (table 10). Types with thick organic horizons and little mineral soil exposure following trampling usually experienced the least compaction. Soil compaction was least severe in ABLA/CLUN and most severe on the ABLA/VACA, PSME/SYAL, and ABLA/XETE types. Organic horizons cushion the underlying mineral soil from the pressures of trampling, reducing compaction.

Recovery

Penetration resistance decreased after trampling was curtailed, indicating recovery from compaction. For all habitat types and trampling intensities, mean resistance decreased from 2.2 tons/ft² (2.2 kg/cm²) immediately after three seasons of trampling to 1.8 tons/ft² (1.8 kg/cm²), 1.8 tons/ft² (1.8 kg/cm²), and 1.3 tons/ft² (1.3 kg/cm²), after the first, second, and third year of recovery. Mean resistance on controls varied between 0.6 and 0.8 ton/ft² (0.6 and 0.8 kg/cm²). The apparent lack of recovery during the second year of recovery reflected abnormally dry soils following a season of drought. Penetration resistance tends to increase as soil moisture decreases, even if soil compaction remains constant.

Although compaction levels have decreased steadily, compaction was still high after 3 years of recovery. Three years after trampling ceased, the penetration resistance of the lanes with 1,600 passes per year was still almost three times higher than that on controls. Only in the FESC-FEID type did several of the trampled lanes have resistances as low as controls (table 11).

Recovery rates varied between habitat types (fig. 23). Least recovery occurred in ABLA/CLUN, the type that experienced the least compaction. PSME/SYAL and FESC-FEID recovered the most. Because FESC-FEID recovered greatly after experiencing only moderate compaction, it had the highest level of recovery (penetration resistance

Table 10—Increase[1] in soil penetration resistance after three seasons of trampling

Number of passes per year	Habitat type						All habitat types
	ABLA/VACA	PSME/SYAL	ABLA/XETE	ABLA/CLUN-VACA	FESC-FEID	ABLA/CLUN	
	kg/cm²						
0	0[a]	0[a]	0[a]	0[a]	0[a]	0[a]	0
5	0.2[a]	0.2[a]	0.2[a]	0.2[a]	0.2[a]	0.3[a]	0.2
15	.5[a]	.3[a]	.7[a]	.4[a]	.4[a]	.3[a]	.4
25	.6[a]	.3[a]	.7[a]	.4[a]	.5[a]	.2[a]	.5
40	.7[a]	.4[a]	.6[a]	1.1[a]	.7[a]	.3[a]	.6
75	1.1[a]	.8[a]	1.0[a]	.8[a]	.4[a]	.4[a]	.8
80	1.7[b]	.9[a]	2.0[b]	.7[a]	.8[a]	.6[a]	1.2
100	1.4[a]	1.1[a]	1.5[a]	.7[a]	1.0[a]	.5[a]	1.1
200	1.8[a]	1.6[a]	1.7[a]	1.2[a]	1.3[a]	1.0[a]	1.5
300	2.6[c]	2.4[c]	2.4[c]	1.6[b]	1.2[ab]	1.0[a]	2.0
400	3.5[d]	2.4[bc]	2.6[bc]	2.6[bc]	1.8[ab]	1.2[a]	2.4
600	3.2[d]	3.0[d]	2.8[cd]	1.8[b]	2.2[bc]	.9[a]	2.5
800	3.8[b]	2.7[a]	2.3[a]	2.1[a]	2.3[a]	1.9[a]	2.6
900	3.3[c]	2.6[bc]	2.6[bc]	2.7[bc]	1.8[b]	1.2[a]	2.5
1,200	3.3[bc]	3.8[c]	2.7[b]	3.2[bc]	2.0[a]	1.9[a]	2.9
1,600	3.5[c]	3.5[c]	3.1[bc]	2.6[ab]	2.7[ab]	2.3[a]	3.1
Mean of all treatments	2.0[d]	1.7[c]	1.7[cd]	1.4[bc]	1.2[ab]	.9[a]	1.5

[1]Increase is the difference in penetration resistance between control and treatment plots. Any two values in the same row followed by the same letter are not significantly different (Duncan's multiple range test, $p = 0.05$).

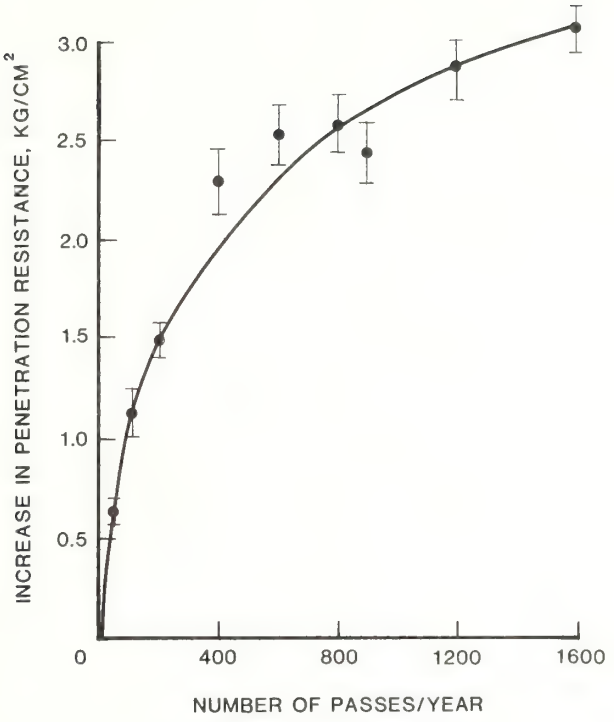


Figure 22—Relationship between trampling intensity and increase in penetration resistance. Increase is the difference in penetration resistance between control and treatments. Data are the mean of all habitat types. Vertical bars are ±1 standard error.

3 years after trampling ceased was lowest). Other types were intermediate in response. Estimates of how long it would take for the penetration resistance of the most heavily trampled lanes to recover to within 10 percent of that on undisturbed controls range from 5 to 6 years in FESC-FEID to about 12 to 15 years in ABLA/XETE, PSME/SYAL, and ABLA/CLUN-VACA.

What Determines Amount of Deterioration and Recovery?

Both of the controlled variables, trampling intensity and habitat type, influenced amount of soil compaction (deterioration). Compaction was generally less severe on sites that retained thick organic horizons after trampling. Compaction on lanes with 600 passes per year in ABLA/CLUN, which experienced no exposure of mineral soil, was less than one-third of that in types that experienced substantial soil exposure. Compaction also increased with trampling intensity, both because the pressures exerted increase with trampling intensity and because organic horizons are thinner and less complete where trampling intensity is high. Nevertheless, amount of compaction does level off at high trampling intensities, despite linear increases in soil exposure at heavy trampling intensities.

Amount of recovery is most strongly influenced by trampling intensity (fig. 24). The rate and amount of recovery increases as trampling intensity increases.

Table 11—Increase[1] in penetration resistance 3 years after trampling ceased

Number of passes per year	Habitat type					All habitat types
	ABLA/ XETE	ABLA/ CLUN-VACA	PSME/ SYAL	ABLA/ CLUN	FESC- FEID	
	kg/cm²					
0	0[a]	0[a]	0[a]	0[a]	0[a]	0
5	0.3[b]	0.2[ab]	0[a]	0[a]	0[a]	0.1
15	.4[b]	.4[b]	0[ab]	0.3[b]	–0.1[a]	.1
25	.6[b]	.2[ab]	0.1[ab]	.1[ab]	0[a]	.2
40	.2[a]	.3[a]	.3[a]	.4[a]	.1[a]	.2
75	.4[b]	.4[b]	0[a]	.3[b]	–.2[a]	.1
80	.4[b]	.2[b]	.4[b]	.3[b]	–.1[a]	.3
100	.6[b]	.6[b]	.3[ab]	.3[ab]	0[a]	.3
200	.6[b]	1.0[b]	.6[b]	.5[b]	–.1[a]	.4
300	1.1[b]	.9[b]	.8[b]	.7[b]	.1[a]	.7
400	.9[b]	.9[b]	.8[b]	.9[b]	.4[a]	.7
600	1.3[b]	1.2[b]	1.0[b]	1.0[b]	.4[a]	1.0
800	1.0[bc]	1.6[c]	.9[b]	1.0[bc]	.5[a]	.9
900	1.3[c]	1.1[bc]	.9[bc]	.7[b]	.3[a]	.8
1,200	1.7[b]	1.2[b]	1.4[b]	1.1[b]	.4[a]	1.3
1,600	1.7[bc]	2.2[c]	1.3[bc]	1.1[b]	.4[a]	1.3
Mean of all treatments	.8[c]	.8[bc]	.6[b]	.5[b]	.1[a]	.5

[1]Increase is the difference in penetration resistance between control and treatment plots. Any two values in the same row followed by the same letter are not significantly different (Duncan's multiple range test, $p = 0.05$).

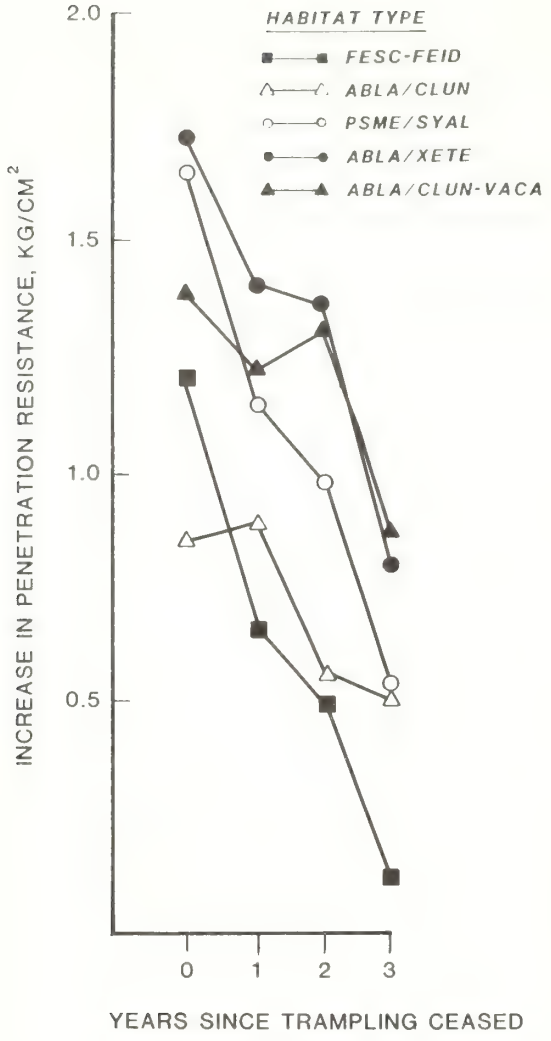


Figure 23—Differences among habitat types in recovery of compacted soils following the cessation of trampling. Increase is the difference in penetration resistance between control and treatments. Data are the mean of all trampling intensities. All standard errors were 0.13 kg/cm² or less.

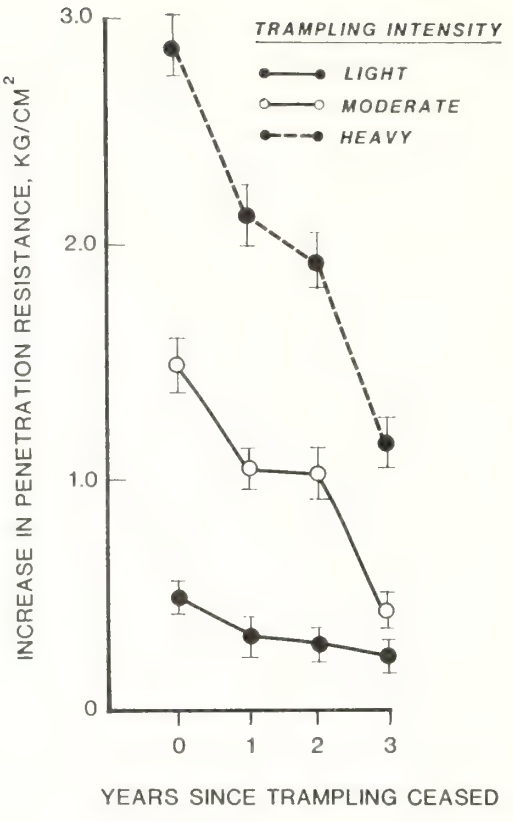


Figure 24—Recovery of compacted mineral soil following cessation of trampling at light (median of 15, 25, and 40 passes per year), moderate (100, 200, and 300 passes per year), and heavy (median of 900, 1,200, and 1,600 passes per year) intensities. Increase is the difference in penetration resistance between control and treatments. Data are the mean of all habitat types. Vertical bars are ±1 standard error.

Those sites that experienced the most compaction generally recovered the most. There is no evidence to suggest that there is a threshold beyond which the ability to recover declines. This response is similar to that of the organic horizon and contrasts with the response of vegetation.

MANAGEMENT IMPLICATIONS

The results of these experiments can be used to predict the effects of cross-country hiking and of trampling on campsites; the difficulty lies in correlating these treatments with recreational use. The impacts associated with a given number of passes per year would be the same as those caused by a comparable number of hikers, if they walked single file. Where hikers spread out, prediction is less precise. The effect of a given number of hikers can be approximated by dividing the number of hikers by a factor (related to how much hikers spread out) and looking up the effects of that many passes per year. For example, if 300 people per year follow a route that allows a moderate amount of spreading out, perhaps only one-third of the hikers follow the same route. In this case, the effects of 300 people per year would approximate those observed on the lane with 100 passes per year. While this need to compensate for hikers spreading out interjects a source of inaccuracy, the results of these experiments improve the ability to predict the effects of cross-country hikers. Results cannot be readily applied to hikers on trails because constructed trails are so different from undisturbed environments.

The effects of trampling on campsites can also be predicted. Many campsite impacts (for example, tree damage and fire building) are unrelated, but most of the loss of vegetation and organic matter and the compaction of soils on campsites results from trampling roughly comparable to that administered in these experiments. These impacts can be predicted. Observations and limited experimentation (Cole 1985, 1987a) indicate that the trampling impacts caused by a typical party of two to three people, in one night of camping, are similar to those caused by 75 to 150 experimental passes. This would apply to the central portion of the campsite, where use is heaviest.

These correlations allow us to estimate how much camping and hiking different sites can tolerate before deteriorating to unacceptable levels. The predictions should be treated as rough estimates, subject to several sources of inaccuracy. The translation from number of passes to nights of camping and number of hikers is rough. Moreover, recovery levels are overestimated because trampling occurred for only 3 years and vegetation could spread from little-disturbed buffer strips a short distance away. Finally, it is not clear how site-specific results are. Mineral soil exposure definitely would have been more pronounced if plots had been on slopes rather than on flat topography. This is important to remember when using these results to predict the effects of cross-country hikers.

In the following section the likely effects of various numbers of hikers walking single-file and of nights of camping will be described for the three habitat types with the most divergent responses—FESC-FEID, ABLA/CLUN, and ABLA/XETE. Likely responses of the ABLA/VACA, PSME/SYAL, and ABLA/CLUN-VACA types will usually fall between those of the ABLA/CLUN and ABLA/XETE types.

The FESC-FEID Habitat Type

One Hundred Hikers; One Night of Camping—A previously undisturbed site crossed by 100 hikers or camped on for one night is likely to experience some flattening of vegetation and short-term loss of forbs, but vegetational cover remains complete, no mineral soil is exposed, and soil compaction is minimal. Recovery of vegetation is complete by the following year.

One Hundred Hikers per Year; One Night of Camping per Year—Continuation of this level of use will cause slight vegetation loss, soil exposure, and soil compaction. The only visual evidence to users will be flattening of the vegetation, although complete recovery will take several years.

Five Hundred Hikers per Year; Five Nights of Camping per Year—This will result in loss of about 50 percent of the vegetation cover, slight exposure of mineral soil, and substantial soil compaction. If use is curtailed, vegetational cover and litter cover may be completely restored within 3 years, but some cover loss and soil compaction remain.

One Thousand to 1,500 Hikers per Year; 10 to 15 Nights of Camping per Year—This will eliminate most, but not all, vegetational cover; resistant clumps of *Festuca scabrella* survive. Mineral soil exposure exceeds 10 percent and soils are highly compacted. One year after use is curtailed, vegetational cover will exceed 50 percent and soil compaction will have been reduced substantially, but soil exposure remains high. Most visual evidence of use should disappear within 3 years. (Remember that recovery may be less rapid where use has occurred for more than 3 years.)

The ABLA/CLUN Habitat Type

One Hundred Hikers; One Night of Camping—This will eliminate most of the vegetation, but no mineral soil will be exposed and soil compaction will be negligible. Most visual evidence of impact will disappear in 1 year, although a number of species will have reduced cover.

One Hundred Hikers per Year; One Night of Camping per Year—This will eliminate most of the vegetation, but no mineral soil is exposed and soil compaction is low. Vegetational cover will exceed 50 percent 1 year after use is curtailed and will appear undisturbed after 3 years of recovery, although complete recovery of all species has not occurred.

Five Hundred Hikers per Year; Five Nights of Camping per Year—Only a few vegetation remnants survive. Although there is still no mineral soil exposure, substantial soil compaction occurs. Vegetational cover will be about 50 percent 1 year after use is curtailed, but little reduction in compaction occurs. After 3 years of recovery, vegetational cover is nearly complete, although some loss is still evident and soil compaction is still substantial.

One Thousand to 1,500 Hikers per Year; 10 to 15 Nights of Camping per Year—All vegetation is eliminated and soil compaction is moderately high, although no mineral soil is exposed. Little recovery occurs in 1 year. After 3 years of recovery most of the site is covered with vegetation, although it is noticeably sparse and a path is still evident. Compaction levels have moderated but are still substantial. (Again, recovery may be less rapid where use has occurred for more than 3 years.)

The ABLA/XETE Habitat Type

One Hundred Hikers; One Night of Camping—Loss of vegetation and a path are evident, although most of the site remains vegetated. Some mineral soil is exposed and substantial compaction occurs. Little vegetational recovery occurs in 1 year, although compaction levels are reduced.

One Hundred Hikers per Year; One Night of Camping per Year—About one-half of the vegetation is lost, some mineral soil is exposed, and soil compaction is moderately high. One year after use is curtailed, the only pronounced change is a reduction in compaction. After 3 years of recovery, little visual evidence of disturbance remains, although compaction levels are still elevated and some species have not regained complete cover.

Five Hundred Hikers per Year; Five Nights of Camping per Year—Most, but not all, vegetation is eliminated, mineral soil exposure exceeds 5 percent and is visually evident, and soil compaction is high. Little recovery occurs in one season. After 3 years of recovery,

most of the path/site is vegetated, although vegetation is noticeably sparse. Litter cover is nearly complete, but compaction levels remain substantial.

One Thousand to 1,500 Hikers per Year; 10 to 15 Nights of Camping per Year—Most, but not all, vegetation is lost, mineral soil is widespread (about 15 to 20 percent), and soil compaction is severe. Aside from a sizable decrease in mineral soil exposure, little recovery occurs in 1 year. After 3 years of recovery, a sparse vegetation covers about 50 percent of the path/site, litter cover is nearly complete, and soil compaction is still moderately high. (Again, recovery may be less rapid where use has occurred for more than 3 years.)

One obvious conclusion is how little use these sites can sustain and still recover in one growing season. Only the FESC-FEID grassland can tolerate one night of camping per year without experiencing deterioration from which it cannot recover in 1 year; it can tolerate three to four nights per year. Therefore, if managers are attempting to keep vegetation damage to a level where it can recover in a year (this is a frequently mentioned objective in remote, relatively undisturbed portions of wilderness), they should convince people to camp on grasslands rather than in the forests. Even grassland sites should not be used if damage is apparent, and use levels must be low enough so that no site is used more than a few times per year. Cross-country hikers should also be encouraged to walk through grassland rather than forest. While hundreds of hikers per year can cross grasslands and have no long-term effect, as few as 20 to 25 hikers per year, if they walk single-file, can damage the vegetation of the forested habitat types to the point where recovery is not complete in one season. In areas where hikers cannot avoid forest vegetation and managers want to avoid creation of new trails, use levels must be low enough so that no more than 20 to 25 hikers per year are likely to follow the same route. If hikers spread out rather than walk single-file, areas can accommodate more use before impacts become noticeable.

Where use is heavy and long-term vegetation damage is inevitable, managers might want to limit use to levels where mineral soil exposure will not be substantial—for example, where soil exposure is confined to less than 5 percent of the concentrated-use part of the site. The maximum number of passes per year that caused no more than a 5 percent increase in mineral soil exposure was 1,600 in ABLA/CLUN and ABLA/VACA, 900 in ABLA/CLUN-VACA, 800 in FESC-FEID, 400 in PSME/SYAL, and 200 in ABLA/XETE. ABLA/CLUN and ABLA/VACA are clearly the most durable locations; they can tolerate a week or two of camping per year or be walked on by over 1,000 hikers per year (provided there is no slope, as was the case in these experiments). Even one night of camping or several hundred hikers is likely to expose mineral soil in the ABLA/XETE type, however.

As has been found in many other studies, these results provide dramatic evidence of the inevitability of impact, particularly to vegetation, wherever people regularly go. This highlights the difficulty of controlling impact through use limitation, as well as the need to concentrate use, in frequently used areas, so that the number of impacted places is limited. Data from this study can be useful in identifying use levels above which concentration is necessary and below which dispersal of use over many sites is feasible as a means of reducing impact. The asymptotic nature of most use/impact relationships permits the identification of use thresholds, located at the trampling intensity where the curves describing these relationships first approach the asymptote. Above these thresholds, use limitation has little effect, amount of impact is not strongly influenced by trampling intensity, and concentration of use is necessary to control impact. Below these thresholds, amount of impact **is** strongly influenced by amount of use, and dispersal of use, to minimize trampling intensity on all sites, is desirable.

For example, figure 25 shows a curve describing the relationship between trampling intensity and vegetational cover in the ABLA/CLUN type. The use threshold is somewhere between 200 and 400 passes per year. Above 400 passes per year, increased trampling has little detrimental effect, while reductions in intensity below 200 passes per year have positive benefits. In other words, if use levels on sites in ABLA/CLUN can be kept below 200 passes per year (about one night of camping per year or the passage of several hundred hikers, walking single-file) it would be valuable to disperse users so that campsites and travel routes are used as infrequently as possible. Campers should select apparently undisturbed sites, and hikers should spread out and avoid trampling the same route. If use is so heavy that sites are likely to be used more than one night per year, either use must be reduced or camping should be concentrated on a few sites. Similarly, if more than several hundred hikers are likely to follow the same route through these forests, trails will develop and it would be best to either construct an "official" trail or reduce use.

Use thresholds vary with impact parameter and habitat type. There were no thresholds for mineral soil exposure because exposure increased linearly with increases in trampling intensity. Use thresholds for the other parameters are presented in table 12. Thresholds are always lowest for vegetation loss. The critical implication of this is that use thresholds for vegetation loss will generally determine whether concentration or dispersal is appropriate. Concentration of camping is best except where use of sites can be kept below seven to eight nights per year in the FESC-FEID grassland, two nights per year in ABLA/XETE, and one night per year in the other forested types. As noted earlier, even these levels of use will cause pronounced impact, so use levels should be as low as possible.

It is almost always best to concentrate use of regularly used places on trails and campsites. Because concentrated use will eliminate even the most resistant vegetation, vegetational resistance is not relevant to the location of concentrated-use campsites. The best locations for such sites, aside from bedrock, are places where organic horizons are thick (for example, in ABLA/CLUN); this will minimize mineral soil exposure and soil compaction. Trail location will be guided by concern for many factors that were not controlled in these experiments, such as soil moisture and erosiveness.

Dispersal is desirable only where use levels can be kept below those defined by use thresholds for vegetation cover (table 12). Even with these use levels, dispersal may cause problems if users do not practice low-impact camping

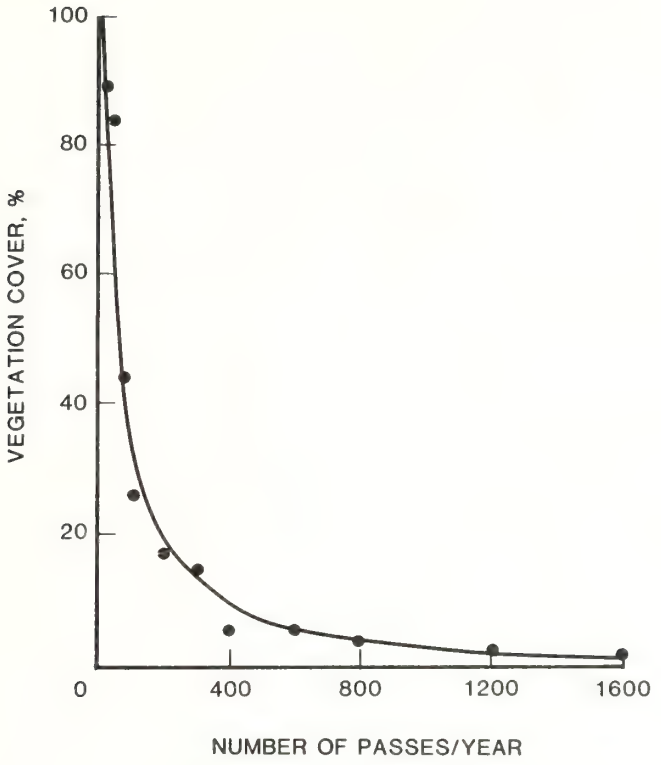


Figure 25—The relationship between vegetational cover and trampling intensity in the *Abies lasiocarpa/Clintonia uniflora* habitat type after three seasons of trampling. Vegetational cover is the proportion of original cover present after trampling (based on a single estimate of vegetation cover), adjusted for changes on controls.

techniques, so education of users and monitoring of impacts are particularly important. Dispersal should be implemented by convincing people not to camp or hike where previous disturbance is evident. Of vegetated sites, it is best to use grasslands because they can tolerate the most use. The species classifications in tables 6 and 7 can also be used to predict which sites will be most resistant to vegetation loss and, therefore, the best sites for dispersed use. Nonvegetated sites, such as bedrock or beaches, are even better.

These data can also be used to compare deterioration and recovery rates. None of these habitat types could recover completely from any trampling intensity within the period of time over which trampling occurred. This applied to both one season of trampling and recovery and three seasons of trampling and recovery. This provides further evidence that there is little opportunity to minimize impact through alternately opening and closing sites. Rotation of use among a large number of sites will effectively limit impact only where use levels are so low that sites are never allowed to deteriorate substantially. Such a rotation system is identical to the use dispersal strategy discussed previously. Rest-rotation of regularly used and well-impacted sites is not feasible in montane ecosystems such as these, and is even less feasible in less resilient environments such as subalpine ecosystems.

METHODOLOGICAL IMPLICATIONS

This study was the most detailed experimental trampling study that has been conducted. Sources of complexity included varying frequency of trampling (the number of times per season trampling treatments were applied) as well as trampling intensity, the large number of observation times (twice a year for three seasons of trampling and once a year for 3 years of recovery), the number of impact parameters measured, and the number of habitat types studied. This complexity was designed into the study because few of these variables had been adequately examined before. Although much was learned, the study also generated more data than could be readily analyzed and, in hindsight, much of this complexity and detail was unnecessary.

Table 12—Trampling intensities below which reductions in intensity will reduce impact

Habitat type[1]	Impact parameter		
	Vegetation cover	Species persistence	Increase in penetration resistance
	Number of passes per year		
GRASSLAND			
FESC-FEID	1,200	>1,600	>1,600
FOREST			
ABLA/XETE	400	1,200	600
PSME/SYAL	200	800	1,200
ABLA/VACA	200	600	400
ABLA/CLUN	200	400	>1,600
ABLA/CLUN-VACA	200	600	1,200

[1]See table 1 for definitions.

The frequency of trampling had no consistent and substantial effect on amount of impact. Bayfield (1979) arrived at the same conclusion. Therefore, it is often valid to apply trampling treatments at one time and assume that the effect is similar to that of the same number of passes spread out over time. This will greatly reduce the time spent trampling. Only when trying to simulate trampling of vegetation in various phenological stages or during very different seasons is frequency of trampling likely to be an important variable.

The range of trampling intensities used was close to ideal, however. Although the highest intensities were not necessary to examine vegetation response, even higher trampling intensities would have been desirable to examine the response of organic horizons.

The examination of a range of habitat types was also useful, particularly in evaluating the magnitude of differences in response. This provided valuable information on how significant differences in site durability were and at what trampling intensities differences were most substantial. An expansion of the range of vegetation types and environmental factors studied seems highly desirable. Perhaps this could be done by independent investigators utilizing a standardized experimental procedure.

The continuation of the experiment over several seasons with many observation times provided some valuable insights. It provided measures of both short- and long-term recovery. It also showed that to simulate continuing recreational use, trampling treatments need to be administered for at least 2 years. Single-season trampling experiments, at least in these habitat types, would have underestimated the impact caused by long-term use, particularly on resistant sites. They would have overestimated differences among sites in susceptibility to vegetation impact and underestimated differences in susceptibility to soil exposure and compaction.

It is my contention, however, that there are more appropriate means of studying the impacts associated with prolonged recreational use and subsequent recovery. In these experiments vegetation recovery occurred more rapidly than it would have on recreation sites because much of the revegetation on trampled lanes spread from adjacent relatively undisturbed buffer strips. Moreover, there was evidence that the ability to recover was diminishing after several seasons of heavy trampling. More than three seasons of trampling may be required before further trampling will have no additional effect on the ability to recover. Closure of existing recreation sites—while replete with its own set of problems—seems to be a more appropriate method for studying recovery of long-used recreation sites.

Prolonged use of almost any site will eliminate most of the vegetation. Therefore, the impacts of most concern where use is prolonged will be soil impacts. These can be usefully studied in an experimental manner, but control and stratification of variables such as soil moisture, soil texture, and slope are usually more important than vegetation type (although vegetation may be correlated with these variables). This calls for either very different types of experiments or studies that monitor changes on recently opened recreation sites.

Experimental trampling of different vegetation types seems most useful in examining the short-term effects and subsequent recovery of relatively light trampling. Differences in vegetation loss among vegetation types are most pronounced at moderately light trampling intensities (100 to 300 passes per year or one to two nights of camping per year) and after just one season of trampling. This type of trampling simulates the effects of various levels of highly dispersed trampling; results can be used to determine appropriate use levels for concentrating or dispersing use.

The most useful aspect of experimental trampling, then, is to study its effects on vegetation, with perhaps four to five incremental increases in number of passes from 0 to 500 or (in resistant vegetation) 1,000 passes. Immediate effects, effects several weeks later (to identify delayed damage), and effects a year later should be measured. Such tests should suffice to identify use thresholds, as well as how much use a site can tolerate and still recover in 1 year. From these data managers can establish use limits that will maintain remote, lightly used areas in essentially pristine condition. They can also inform users of the most durable sites for camping and travel. Other types of information are needed to set use limits or develop other management strategies for more heavily used places where more pronounced impacts are inevitable.

REFERENCES

Bayfield, Neil G. 1979. Recovery of four montane heath communities on Cairngorm, Scotland, from disturbance by trampling. Biological Conservation. 15: 165-179.

Bell, Katherine L.; Bliss, Lawrence C. 1973. Alpine disturbance studies; Olympic National Park, U.S.A. Biological Conservation. 5: 25-32.

Cole, David N. 1985. Recreational trampling effects on six habitat types in western Montana. Res. Pap. INT-350. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 43 p.

Cole, David N. 1987a. Effects of three seasons of trampling on five montane forest communities and a grassland in western Montana, U.S.A. Biological Conservation. 40: 219-244.

Cole, David N. 1987b. Research on soil and vegetation in wilderness: a state-of-knowledge review. In: Lucas, Robert C., compiler. Proceedings— national wilderness research conference: issues, state-of-knowledge, and future directions; 1985 July 23-26; Fort Collins, CO. Gen. Tech. Rep. INT-220. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 135-177.

Grime, J. P. 1973. Control of species density in herbaceous vegetation. Journal of Environmental Management. 1: 151-167.

Hitchcock, C. Leo; Cronquist, Arthur. 1973. Flora of the Pacific Northwest. Seattle: University of Washington Press. 730 p.

Holmes, Daniel O.; Dobson, Heidi E. M. 1976. Ecological carrying capacity research: Yosemite National Park. Part I. The effects of human trampling and urine on subalpine vegetation: a survey of past and present backcountry use and the ecological carrying capacity of wilderness. PB-270-955. Springfield, VA: U.S. Department of Commerce, National Technical Information Service. 247 p.

Kuss, Fred R.; Graefe, Alan R. 1985. Effects of recreation trampling on natural area vegetation. Journal of Leisure Research. 17: 165-183.

Liddle, M. J. 1975a. A selective review of the ecological effects of human trampling on natural ecosystems. Biological Conservation. 7: 17-36.

Liddle, M. J. 1975b. A theoretical relationship between the primary productivity of vegetation and its ability to tolerate trampling. Biological Conservation. 8: 251-255.

Mueggler, W. F.; Stewart, W. L. 1980. Grassland and shrubland habitat types of western Montana. Gen. Tech. Rep. INT-66. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 154 p.

Pfister, Robert D.; Kovalchik, Bernard L.; Arno, Stephen F.; Presby, Richard C. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 174 p.

Price, Martin F. 1985. Impacts of recreational activities on alpine vegetation in western North America. Mountain Research and Development. 5: 263-277.

Rees, Joan; Tivy, Joy. 1978. Recreational impact on Scottish lochshore wetlands. Journal of Biogeography. 5: 93-108.

Schreiner, Edward George. 1973. Vegetation dynamics and human trampling in three subalpine communities of Olympic National Park, Washington. Seattle: University of Washington. 150 p. Thesis.

Soil Survey Staff. 1975. Soil taxonomy. Agric. Handb. 436. Washington, DC: U.S. Department of Agriculture, Soil Conservation Service. 754 p.

Strand, Steve. 1979. Recovery of Sierran meadows after trampling by pack stock. In: Stanley, J. T., Jr.; Harvey, H. T.; Hartesveldt, R. J., eds. A report on the wilderness impact study: the effects of human recreational activities on wilderness ecosystems with special emphasis on Sierra Club wilderness outings in the Sierra Nevada. San Francisco: Sierra Club Outing Committee: 88-93.

Willard, Beatrice E.; Marr, John W. 1970. Effects of human activities on alpine tundra ecosystems in Rocky Mountain National Park, Colorado. Biological Conservation. 2: 257-265.

☆ U.S. GOVERNMENT PRINTING OFFICE:1988-573-039/61059

Cole, David N. 1988. Disturbance and recovery of trampled montane grassland and forests in Montana. Res. Pap. INT-389. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 37 p.

Five forested vegetation types and one grassland in western Montana were subjected to experimental trampling. Changes in vegetational cover, number of species, mineral soil exposure, and soil penetration resistance were examined, as were responses of individual species. Deterioration and recovery following various levels of trampling are described, and factors that influence resistance and resilience are noted. Management implications are discussed.

KEYWORDS: ecological impact, trampling, wilderness, backcountry management, habitat types, damage

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-390

April 1988

Soil Characteristics as an Aid to Identifying Forest Habitat Types in Northern Idaho

Kenneth E. Neiman, Jr.

AUG 17 1988
PUBLIC DOCUMENTS

THE AUTHOR

KENNETH E. NEIMAN, JR., is a private forest ecology/soils consultant living in Moscow, ID. From 1981 to 1986, he was forest ecologist assigned to the research work unit on silviculture of cedar, hemlock, grand fir and Douglas-fir of the Northern Rocky Mountains, Intermountain Research Station, Moscow, ID. Dr. Neiman received his B.S. degree in 1975 in range management and his M.S. degree in 1977 in forest and range ecology—both degrees from Washington State University. He received a Ph.D. degree in forest ecology in 1986 from the University of Idaho. This paper represents a portion of the research presented in his dissertation.

RESEARCH SUMMARY

Scientists have long hypothesized that soils and plant communities have predictable relationships. High correlation between soil properties and shrub-steppe plant associations has been repeatedly documented, but studies in forested vegetation have produced conflicting results. The objectives of this study were to investigate: spatial patterns of numerically derived taxonomic soil units; relationships between soil taxonomic units and plant associations; and identifying soil characteristics for aid in forest habitat type identification.

Vegetation, soil, and site information were collected on 89 sites within six similar habitat types of the *Abies grandis, Thuja plicata*, and *Tsuga heterophylla* series. Univariate and multivariate statistical analyses were used to evaluate naturally occurring patterns within the soil data and between soil and vegetation data. Four ordination techniques were used to explore potential soil pattern delineation. Factor analysis and descriptive discriminant analysis techniques were employed to identify physical soil property descriptors for use in habitat type discriminant function formulas.

Numerical patterns were not discernible among the physical soil characteristics. Analysis of relationships between forest habitat types and soil taxonomic units—Order, Suborder, Great Group, and Family—proved fruitless. Four soil characteristics were identified as useful for classifying habitat type when used in conjunction with site and vegetation data. Formulas developed from discriminant functions are given for use in the field as an aid to forest habitat type classification in northern Idaho.

The use of habitat types for refinement of silvicultural prescriptions and site productivity assessment in northern Idaho has proven to be highly valuable to forest resource managers. This study indicates that further delineation of these units, based on soil variation, will allow for greater accuracy in predicting site capabilities and response to disturbance.

Soil Characteristics as an Aid to Identifying Forest Habitat Types in Northern Idaho

Kenneth E. Neiman, Jr.

INTRODUCTION

Habitat types (after Daubenmire 1968) and other vegetation-based land classification systems (Cooper and others 1987; Daubenmire and Daubenmire 1968; Hall 1973; Hironaka and others 1983; Mueggler and Stewart 1980; Pfister and others 1977; Steele and others 1981, 1983; Tisdale 1979) have been adopted for use throughout the Northern Rocky Mountains by the U.S. Department of Agriculture, Forest Service, and other Federal and State agencies. These systems rely on knowledge of the existing floristics for identification of "climax" or long-term stable plant associations. On forested lands that have not been severely disturbed, habitat types can be identified with relative ease by use of species presence lists. But as land is disrupted by forest management, habitat types will have to be identified from a secondary successional plant community, often having little floristic similarity to its climax community. Even highly trained plant ecologists find this to be a speculative and frustrating task. Land managers and scientists need to classify seral communities and also to develop a means for extrapolating seral community types to their respective habitat types with the aid of both biotic and abiotic factors.

In studies of abiotic site factors, Jenny (1941, 1980) theorized that soil development is a function of climate, parent material, relief, and potential organisms interacting over time. Major (1951) felt that species composition of vegetation is a similar function of the same five factors. Although soil and vegetation both appear to respond to the same "functional factors," this relationship cannot be extended to indicate that soil and vegetation are correlated on a one-to-one basis. Although we find sites with similar vegetational composition, often these do not have similar site characteristics, parent material, or age (Barnes and others 1982; Daubenmire 1968; McCune and Allen 1985; Pfister and Arno 1980). Vegetation responds to both long-term and short-term environmental changes (Daubenmire 1956), but is particularly responsive to extremes of temperature and moisture. Climatic pulses tend to have a minor effect on soil formation processes. Thus, different soils often develop beneath similar plant communities and, conversely, different plant communities occur on what outwardly appear to be similar soils.

In most physical systems, both internal and external sets of independent factors determine the development of individual characteristics. Nowhere is this more observable than in the wide variety of soil horizonations. Whether viewed regionally or locally no two cross sections of soil are exactly alike. Yet, in an attempt to understand this variability, taxonomic systems are devised that identify individuals as members of classification units. Soil taxonomy (USDA SCS 1975), a soil classification system, is based on differentiating characteristics assumed to be the result of independent factors.

Jenny (1941, 1980) described five elements critical to all soil development: climate, in the sense of regional macroclimate; parent material, the basement rock or depositional material from which the soil originates; relief (topography), the slope, aspect, elevation, landform, and related ground water conditions; organisms, the micro- and macro-organisms of plant and animal species potentially available for site occupancy; and time, the zero point being calculated from the initiation of soil formation or since major disturbance to existing conditions.

Jenny (1958, 1980) further described plants as being both dependent and independent variables. The species that dominate the vegetational community will exert their own particular influence on both plant community and soil-forming processes. Thus, with all factors remaining constant except time and natural succession, soil development continues as a reaction to both independent and dependent biotic components.

Many taxonomies have been developed for both plant communities and soils, but little direct analysis of their interrelationships has been attempted. In the Northern Rocky Mountains, only one climax community classification (Tisdale and Bramble-Brodahl 1983) and one successional community classification (Hann 1982) have aggressively attempted to correlate specific plant communities with specific soil and site characteristics.

In two of the major plant community classifications developed for the Inland Northwest (Daubenmire 1970; Daubenmire and Daubenmire 1968) extensive soil profile data were collected in hopes of defining a soil-vegetation relationship. But all such attempts failed due to multiple soil series occurring in one habitat type. Further confusion arose when soil families and Great Groups also did not correlate with plant communities. Daubenmire (1970) recognized the importance of soil factors to vegetation and strongly emphasized "those soil properties suspected of playing important roles in vegetation differentiation are not among the characteristics emphasized in soil classification." Soil moisture and temperature regimes, aeration,

and nutrients are the important attributes for vegetation (Daubenmire 1970; Loucks 1962). None of these are adequately assessed by current soil taxonomic systems.

McCune and Allen (1985) were unable to statistically relate site characteristics to climax tree species along the eastern front of the Bitterroot Range in western Montana. They attributed only 10 percent of the compositional variation to measured site factors, assigning the rest of the variation mostly to historical factors.

Hann (1982) described three site types for both a forested and nonforested habitat type in western Montana. Although all soils classified to two closely associated families, Hann stated that considerable variation was found between sites. He qualitatively describes a number of soil-parent material-environmental conditions which, in his study area, relate very well to differing successional communities and specific habitat types.

In classifying sagebrush-grass habitat types of southern Idaho, Hironaka and others (1983) conducted a more intensive but similar qualitative analysis of the vegetation-soil relationship. Where soil-series-level classifications were available, correlation between the soil series or series-phase and habitat type was discussed. Statistical analysis of the physical and chemical data collected during this study would have greatly increased the knowledge of individual and combined soil characteristics relative to the vegetation being supported. Even without this further analysis, this study is the most intensive of regional plant communities and soil relationships thus far published for the Western United States.

In a study of the major plant communities of the Guadalupe Mountains of Texas and New Mexico, Bunting (1978) conducted an extensive analysis of topoedaphic variables as predictors of potential natural vegetation groups. In addition to physical site and soil descriptions, samples were analyzed for organic matter, pH, NO_3^-, P_2O_5, K_2O, Mg^{++}, Na^+, CaO, total soluble salts, and carbonate reaction. Discriminant function classification of stands achieved 90-95 percent accuracy by using a combination of topographic and edaphic variables.

Tisdale and Bramble-Brodahl (1983) conducted a statistically based, intensive study of vegetation communities and soil along the Salmon and Snake Rivers. On their study area, much reduced in geographic scale compared to either the Hironaka and others (1983) or Bunting (1978) studies, they concluded the currently available vegetation and soil classification systems are not compatible, possibly due to a relative difference in scale. Soil units are divided much more finely than vegetational units. A second part of the Tisdale and Bramble-Brodahl study analyzed 16 individual site and soil factors as independent variables for modeling vegetation-site relationships. Discriminant function classification accuracy ranged from 85 to 100 percent. Of the leading six factors, the most important (elevation and radiation index) were site location and orientation dependent. The other four factors were soil related. They concluded that a satisfactory set of soil-site variables could be developed to identify the habitat type of a site, even though only seral vegetation might be present.

In Major's (1951) factorial approach to plant ecology, the same five functional factors that Jenny applied to soil formation were used as independent formative factors in a vegetation equation. Major concluded ". . .there are no universal correlations between vegetation and soil;. . .soil is not determined by vegetation, vegetation is not determined by soil; vegetation and soil develop concomitantly." I hasten to submit at this point that even though no universal relationships appear to exist between soil and vegetation, it is exactly this concomitant development in a localized area that should provide quantifiable characteristics by which we can understand the plant community and soil-forming processes.

The objectives of this study were: to investigate numerical taxonomic techniques for analysis of patterns of physical soil characteristics; to investigate the relationship between known habitat types and soil units created by numerical taxonomy; and to develop the ability to predict habitat type using physical soil characteristics. Due to an acknowledged incompatibility of classification systems, this study, unlike those of Daubenmire and Hironaka and others, did not dwell on attempts to correlate habitat types and soil family or series units. With knowledge of the correlations between climax vegetation, soil, and site characteristics within a specific geographic region, we should be able to more accurately classify any given site within that region to habitat type and phase. This will also improve the ability to identify highly disturbed seral vegetation stages to habitat type and phase and more accurately position them within their successional development pathway.

THE STUDY AREA

The study area comprised northern Idaho from the Salmon River to the Canadian border (fig. 1). Sampling was done on five National Forests (Kaniksu,

Figure 1—Study area comprised Idaho panhandle north of the Salmon River.

Coeur d'Alene, St. Joe, Clearwater, and Nez Perce), and on forested lands of the Idaho Department of Lands and private properties.

Setting

The physical settings of the region vary from low-lying riverine valleys, 300 m above sea level, to glacial trenches, 550 m above sea level, to six major mountain ranges (Selkirk, Purcell, Cabinet, Coeur d'Alene, Clearwater, and Bitterroot Mountains) having elevations as high as 2,745 m. Sampling was mainly restricted to a midelevational zone in this region, ranging from 550 to 1,400 m above sea level.

The macroclimatic regime of northern Idaho is an inland expression of the Pacific Coast maritime climate (Ross and Savage 1967). Estimates for precipitation at sample locations range from 500 to 1,270 mm (Pacific Northwest River Basin Commission 1969); the actual values are dependent on elevation, north-south and east-west location, and position relative to orographically influenced precipitation patterns. Generally, precipitation occurs between October and May. The June through September period averages less than 25 mm rainfall per month. The average monthly ambient temperatures for these sites are equally variable. Mean summer temperatures range from 29 to 36 °C and mean winter temperatures range from –2 to –10 °C, with maximum extremes that range from 41 to –50 °C (USDC NOAA 1985). Although the aboveground climatic conditions are extremely variable, the presence of complete snow cover during winter months creates a moderate soil environment in which soil temperature regimes (USDA SCS 1975) are frigid or cryic and soil moisture regimes are generally udic or ustic, with some drier sites having a xeric regime.

Geology

The study area includes two geological provinces. The Columbia Intermontane Province (Thornbury 1965), from the Seven Devils Mountains northward to Moscow, with interfingering as far north as Coeur d'Alene, is characterized by variable thicknesses of wind-deposited silt (loess) that overlies mid- to late-Tertiary Columbia River Plateau basalts, which, in turn, overlie intrusions of early Tertiary Idaho Batholith granite or Precambrian metasediments.

The Northern Rocky Mountains Province covers the remainder of the study area from the southeast and south-central Nez Perce National Forest to the Canadian border. The Clearwater and Coeur d'Alene Mountain ranges are an undifferentiated mass of Precambrian Belt Supergroup metasediments and Idaho Batholith granodiorites and quartz monzonites. The eastern boundary of the study area is formed by the Bitterroot Range, also quite variable in composition of granite, gneiss, and metasediments. North of Pend Oreille Lake, the Selkirk Mountains and the Cabinet Mountains are both composed of Belt Supergroup metasediments. Tertiary and Quaternary gravel and glacial till deposits occur sporadically throughout the region. Major deposition of till from Pleistocene Epoch continental glaciation occurs at all elevations north of Sandpoint (Buol and others 1980; Ross and Savage 1967). The geologic data collected for habitat type classification in northern Idaho (Cooper and others 1987) identify over two dozen different parent materials.

The region has been subjected to periodic, violent eruptions of volcanos and subsequent deposition of ejecta over wide areas of the Northern Rocky Mountains. Of the three most recent eruptions—Glacier Peak, Mount Mazama, and Mount St. Helens—the most significant was the creation of Crater Lake with the climactic eruption of Mount Mazama about 6,700 years ago. Ash from this event is an important material we now find in both relatively pure and mixed upper soil horizons, as deep as 1 meter, in northern Idaho (Nimlos and Zuuring 1982).

Vegetation

In this study, habitat type is the taxonomic unit used to decribe plant communities (Daubenmire 1968). Habitat type is defined as follows: All the area that now supports, or within recent time has supported, and is still capable of supporting one plant association. A habitat type may encompass quite variable physical characteristics of topography, climate, and soils, yet the effective environment for plant growth and reproduction remains relatively constant. The diagnostic climax plant community (association) acts as an integrator of climate, relief, and soil through factor compensation, allowing for identification of equivalent environments by means of simple floristic lists of diagnostic species.

In the Northern Rocky Mountains, contiguous stands of mesic maritime forests are unique to northern Idaho (Cooper and others 1987; Daubenmire and Daubenmire 1968). These stands are characterized by the climax dominance of the coastal species *Tsuga heterophylla* (Raf.) Sarg. and *Thuja plicata* Donn. ex D. Don. This interpretation of Pacific maritime climatic influence is supported by numerous studies of coastal disjunct species found sporadically throughout northern Idaho (Johnson 1968; Johnson and Steele 1978; Steele 1971). The six habitat types chosen for this study represent the modal environmental conditions for the three overstory species (*T. heterophylla, T. plicata,* and *Abies grandis* [Dougl. ex D. Don] (Lindl.) most directly associated with this maritime climatic anomaly.

METHODS

Sampling Procedures

Vegetation Data—A set of 89 sample plots was selected from those sampled by Cooper and others (1987) as the data base for this study. Because similar studies have shown that a large amount of variation can be expected in the data (Base and Fosberg 1971; Monserud and others 1986; Sondheim and Klinka 1983), sample selection was restricted to six similar habitat types: *Abies grandis/Clintonia uniflora* habitat type-*Clintonia uniflora* phase (ABGR/CLUN-CLUN); *Abies grandis/Asarum caudatum* habitat type-*Asarum caudatum* phase (ABGR/ASCA-ASCA); *Thuja plicata/Clintonia uniflora* habitat type-*Clintonia uniflora* phase (THPL/CLUN-CLUN); *Thuja*

plicata/Asarum caudatum habitat type-*Asarum caudatum* phase (THPL/ASCA-ASCA); *Tsuga heterophylla/Clintonia uniflora* habitat type-*Clintonia uniflora* phase (TSHE/CLUN-CLUN); and *Tsuga heterophylla/Asarum caudatum* habitat type-*Asarum caudatum* phase (TSHE/ASCA-ASCA). Association tables with site data and complete species list with canopy coverage class per species for this study's sample set can be found in Neiman (1986). Site selection technique and rationale for field procedures employed is detailed in Pfister and Arno (1980) and Cooper and others (1987). Hitchcock and Cronquist (1973) was the authority used for all plant nomenclature.

Soil Data—One soil pit was dug per plot at an undisturbed point representative of each stand. Minimum data collected were complete horizonation description (UDSA SCS 1981) and assessment of local parent materials. The set of samples utilized for this study contained 18 separately identified parent materials (table 1). Depth of pits was generally to the first or second C horizon. Time and cost constraints did not allow for excavation to bedrock, or for classification on site to soil family (USDA SCS 1975). Approximately a 1-liter sample of each horizon was collected and returned for laboratory analysis. This analysis consisted of: a verification of tactile textural classification for each horizon; assessment of moist and dry colors under ideal conditions; sieving of samples to determine percentage gravel content by weight; and measurement of pH, using a 1:1 ratio soil:water paste. Because the focus of this study was on field-identifiable characteristics of both vegetation and soil, no nutrient analyses were performed.

Table 1—Parent materials associated with subset of soil-vegetation samples selected for analysis

Rock origin	Parent material
Sedimentary	Sandstone
	Siltstone
	Shale
Metamorphic	Argillite
	Quartzite
	Phyllite
	Schist
	Mica schist
	Gneiss
	Biotite gneiss
Igneous	Basalt
	Quartz monzonite
	Granite
	Biotite granite
Miscellaneous	Alluvium, mixed
	Glacial till, mixed
	Volcanic ash
	Sedimentary, mixed
	Loess

Analytical Procedures

Vegetation Data—Analysis of the vegetation data was performed during the original classification study (Cooper and others 1987) using accepted vegetation ordination techniques. But all plots were reassessed as to their original classification to habitat type and phase.

Soil Data—The hypothesis tested was that soil taxonomic classifications (USDA SCS 1975) have no ecological meaning when applied to forest soil-forest vegetation relationships. A subset of 50 soils formed from coarse-textured parent materials (for example, glacial drift, granite, gneiss, and sandstone) was classified to family taxonomic level by three soil scientists currently active in classification and mapping of soils within the study area (appendix A). These soil taxonomic units were then used to analyze soil-vegetation relationships.

The numerical pattern analysis concentrated on physical characteristics generally identifiable in the field (per instructions in Fosberg and Falen 1983) by non-soil scientist personnel. Individual soil characteristics were quantified for computer analysis and the data entered in an association table format. The initial data set consisted of the following 27 variables for each soil horizon in the vertical sequum:

1. Sequential horizon number – numbered as 1, 2, 3. .
2. Horizon genetic designation – USDA SCS (1981)
3. Depth – to base of horizon in centimeters
4. Boundary – Soil Survey Staff (1981)
5. Dry color – Hue – Munsell (1975)
6. Dry color – Value – Munsell (1975)
7. Dry color – Chroma – Munsell (1975)
8. Moist color – Hue – Munsell (1975)
9. Moist color – Value – Munsell (1975)
10. Moist color – Chroma – Munsell (1975)
11. Structural Grade – USDA SCS (1981)
12. Structural Size – USDA SCS (1981)
13. Structural Shape – USDA SCS (1981)
14. Texture – Gravel – presence/absence coding
15. Texture – % Clay – percentage from textural triangle
16. Texture – % Silt – percentage from textural triangle
17. Texture – % Sand – percentage from textural triangle
18. Available Water Capacity (AWC) – calculated as a function of textural water holding capacity (USDA SCS 1972), horizon depth, presence of volcanic ash, and percentage of coarse fragments per horizon
19. Root abundance – Size fine (USDA SCS 1981)
20. Root abundance – Size medium (USDA SCS 1981)
21. Root abundance – Size coarse (USDA SCS 1981)
22. Coarse fragments – Percent gravel by weight
23. Coarse fragments – Percent cobble by volumetric estimate
24. Coarse fragments – Percent stone by volumetric estimate
25. pH – 1:1 soil:water paste
26. Parent material 1 – coding for parent material
27. Parent material 2 – coding for parent material.

Five additional pedon summarization or site-specific variables were included in the analysis of soil horizon data: Total depth of organic litter layers; total depth of sequum to C horizon; total effective depth, calculated as the summation of each horizon depth times [(100 – percent coarse fragment)/100] down to but not including the C horizon; and total available water capacity, a summation of all horizon AWC's. Soil temperature, moisture regime, or chemical composition data, such as base saturation or cation exchange capacity, were not available for analysis. A complete set of these data and definitions for variables are presented in Neiman (1986).

Data Matrix Design—Since root systems are not generally affected by the minor differences that are significant to soil horizon classification, horizon data was analyzed in a simple sequential order, based on the depth rather than genetic horizon (that is, first, second, third horizon vs. A1, A2, AB, B2, . . .). This design was also dictated by the similarity-dissimilarity index analysis and ordination techniques available, wherein the presence or absence of data for a group of variables is weighted more heavily than are the individual quantitative values. Consider, for example, two pedons identical in all respects except for the presence of a 1-cm-deep A horizon in one of the sequa. Based on the presence-absence relationships in the first set of A horizon variables, ordination techniques would place these two pedons in highly dissimilar positions, whereas the presence of such a shallow A horizon should be subordinate to similarities for variables in the rest of the horizons.

Because categorical names are simply a summarization of horizon characteristics (such as color, texture, . . .), the quantitative data for these characteristics should contain equivalent if not more definitive information. A major problem arises when sequential horizonation rather than genetic horizonation is used for analysis. The problem occurs when one soil description begins with an A horizon and another sample begins with a B horizon. By not using categorical names in the analysis, the ability to differentiate A from B is lost. Forest soils of northern Idaho often do not develop an A horizon, yet when present, it was considered to be potentially significant in analysis of soil-vegetation relationships. Therefore, the first set of 27 horizon characteristics was allotted to only A horizon data, allowing for simplified analysis of presence-absence or quantitative data within only A horizons. For samples having more than one A horizon, a weighted-by-thickness average for all characteristics was used as the single set of A horizon data. The second and subsequent sequential horizon data sets record all other horizonation, and thus are restricted to AB, E, B, C, and R type illuvial and parent material horizons.

Data Analysis—Analysis was divided into three separate processes: The first investigated noise and redundancy of variables in the data set of 27 characteristics per horizon; the second attempted to delineate naturally occurring patterns of soil physical characteristics and assess their relationship to the vegetation types that they support; and the third developed discriminant functions based on soils data that are predictive for habitat type classification. Due to a disparity in both size and units of measure, all variables were standardized to a mean of 1 and a standard deviation of 0.1 (SAS 1982b). All data, raw and standardized, were analyzed for normal, skewed, or bimodal distribution (SAS 1982a) across the entire data set and within sets stratified by habitat type.

Noise was considered as variation in one characteristic being not coordinated with variation in another (Gauch 1982). Noise analysis was restricted to use of means and range data, with only those variables which were constant across the data (and therefore contain no useful information) being removed from further analysis. Correlation analysis of all possible pairs (SAS 1982a) and principal components analysis (Gauch 1977) were used to evaluate redundancy within and relationships between variables across the entire data set and for data stratified by either habitat types or parent material groups. The objective of these analyses was to create a reduced data set of as few independent variables as possible without sacrificing meaningful information.

Pattern analysis was conducted using a series of ordination techniques: polar ordination (Bray and Curtis 1957); principal components analysis (Gauch 1977); two-way indicator species analysis (Hill 1979b); and detrended correspondence analysis (Hill 1979a). All of these techniques are described as dimensionality reduction techniques, but each approaches the problem from a slightly different perspective. All four techniques allow for ordination of both variables and samples in the same analysis, which makes them useful for exploring variable reduction within samples, pattern analysis between samples, and delineation of variables related to patterns of samples.

Vegetation-soil relationships were analyzed using a subset of samples stratified by parent material and further stratified by habitat type. Techniques used to identify significant discriminators were: factor analysis (SAS 1982b); stepwise discriminant analysis (Dixon 1981); and canonical discriminant analysis (SAS 1982b). Using the set of significant variables identified by these programs, classification models based on discriminant functions were developed using discriminant analysis (SAS 1982b).

RESULTS AND DISCUSSION

Data Reduction

Criteria for retaining a variable in the data were as follows: continuous or a class of continuous values; not related to short-term vegetational changes or person-caused disturbance; suited to accurate assessment in the field; requires minimal subjective interpretation; and not influenced by other characteristics. Based on these criteria, a subset of 11 variables per horizon was selected for use in all further analyses. These were: depth; moist color value; moist color chroma; structural size and shape; percentages of clay, silt, gravel, cobble, and stone; and pH. All variables selected are quantified in terms of continuous or classes of continuous units, except for structural shape, which was quantified into categories whose increasing values denote increasing development through illuviation of fine soil material. Univariate analysis indi-

cated a reasonable normality of distribution for all variables.

Initial ordinations were performed using data for all horizons and all 89 pedons. These ordinations produced groupings, based on the presence or absence of data for a single horizon, within a larger sequence of horizons. The number of pedons having data for a fifth and sixth horizon was too few to allow meaningful analysis with those horizons included in the data set. Analysis was then reduced to using the physical characteristics of the first four horizons only. Ordination groups created from this reduced data set still contained very dissimilar soils except for the presence or absence of a thin A horizon or the presence or absence of a fourth horizon. The fourth horizon, when present, contained genetic horizon data that described highly dissimilar B, C, or R type characteristics. Although stratification of the data by parent material was considered to have future utility, further ordination analysis, based on inclusion of the fourth horizon data, was deemed meaningless.

Ordinations were next performed using data from the upper three horizons and only those samples having an A horizon present. A second set of ordinations was then conducted on this same set of samples using only data from the second and third horizons. Comparison of results of these ordinations indicated that very little information was lost due to removal of the A horizon characteristics. All further analyses use only data from the second and third horizons. Because the data consist of the same 11 variables found in two consecutive horizons, a numerical suffix was added to the name of each of the 22 variables to identify the horizon of origin. Even though an A horizon (that is, the first horizon) did not occur in all pedons analyzed, for consistency the suffixes used were 2 and 3.

Widely differing parent materials produce significantly different textural and structural qualities, coarse fragment contents, and pH values, but often do not create differences in color or depth. Data were stratified into coarse-textured vs. fine-textured parent material groups in an attempt to eliminate these confounding factors. Basalt was grouped separately due to its basic properties, as opposed to the acidic nature of the other parent materials. Three groups were created:

Coarse-textured *n*=55	**Fine-textured** *n*=31	**Basalt** *n=3*
Alluvium – coarse	Alluvium – fine	Basalt
Glacial drift	Argillite	
Gneiss	Loess	
Granite	Mica schist	
Mixed sedimentary	Phyllite	
Quartzite	Schist – fine	
Quartz monzonite	Siltite	
Sandstone	Siltstone	
Schist – coarse		

In all cases, volcanic ash, where present, is an overlying amendment to the parent materials.

Pattern Analysis

If a soil-survey-oriented taxonomy can be developed based on a combination of quantifiable and categorical horizon variables, then numerical taxonomic analysis of these variables should assign the same samples to clusters of closely equivalent taxonomic units. One problem created by the monothetic design of the soil taxonomy (USDA SCS 1975) is the emphasis placed on single variables in the delineation of taxonomic units. Two soil sequa similar in all respects except color of the epipedon can vary taxonomically in Order, Suborder, and/or Great Group. The emphasis in this study was not to mimic the currently accepted soil taxonomy, but rather to investigate the classification of polypedons based on multivariate statistical analysis of physical attributes. Because of this approach, the data from individual horizons were not combined into a control section format as used in soil taxonomy (USDA SCS 1975), nor was emphasis in the form of weighting placed on any single variable or set of variables.

As soils are extremely variable and multivariate in character, ordination was selected as the means to summarize and reduce dimensionality of the data (Gauch 1982). Using the four ordination techniques and the 11 variables for each of two horizons as outlined above, no identifiable relationships were discerned between numerically generated soil groupings, soil taxonomic units (using all hierarchical units from Order to Family), and habitat types within the full data set. Further stratification of the data set to reduce internal variation appeared necessary. The coarse-textured parent material group of 55 samples was selected for all further analyses.

Analyses of this reduced data set by three of the ordination techniques ranked samples in similar positions within their respective ordinations (Neiman 1986). Even though the rankings of each technique concurred in a general way, a large amount of variation occurred among the soils. Low eigenvalues of the principal component analysis indicated that only 19 percent of the total variation was explained by the first axis, 62 percent by the first five axes, and 86 percent by the first 10 axes. The so-called "cloud" of sample points in multidimensional space in this case truly lived up to its name. This large amount of unexplained variation in the data indicated that either the selected variables were not suitable for numerical grouping or that identifying soil groups numerically at this level of stratification has no statistical or ecological interpretive power. Yet, the ability to develop consistent rankings of samples by the various analytical techniques indicated a potential to define soil groups. The problem in doing so appears to be the small data set and high variation inherent in soils. Variation could be further reduced by stratifying the coarse-textured parent material group to create a subset containing samples from only granite, quartz monzonite, quartzite, and gneiss. This was not performed due to sample size restrictions.

Soil-Vegetation Relationships

The second objective was to investigate relationships between soil characteristics and forest habitat types. A lack of correlation between the two taxonomic units can be seen in appendix A. If the work of Jenny (1941, 1958) and Major (1951) is correct, then some relatively discrete relationship between the functional factors for soil and

vegetation properties should exist. Because a soil series or series-phase classification was not available for most of the study area, and because the samples had not been chemically analyzed, physical soil characteristics were used to analyze soil-habitat type relationships.

Data were reduced by removing redundant variables. An "inverse" ordination analysis, sometimes called Q-technique (Williams and Lambert 1961), sorts sample-pairs into similarity groups rather than species-pairs. The four "inverse" ordinations of soil characteristics resulted in a high concurrence of rankings of variables (table 2). The assignment of statistical significance to these rankings is meaningless, as the assumptions of linear relationships and independence of terms cannot be met. But almost identical rankings of variables at the extremes of all four ordination techniques identified the same primary group of variables. Structural ped size, ped shape, and coarse fragment content contain variation that appears to be related to internal structure of the data. These relationships were supported by correlation coefficients greater than 0.70 between structural and coarse fragment groups within horizons.

Factor analysis, an eigenvector analysis similar to principal component analysis, describes covariance relationships between two or more variables. If structural ped size and shape, or any other group of variables, are significant covariates, then a single variable is sufficient for analysis. But if a set of variables are not related, then all variables should be retained. Significant covariate relationships were found for seven groups in the first six factors of a varimax rotated factor analysis (SAS 1982b). In Factor 1, the silt and clay content of horizons 2 and 3 were highly related to each other. In Factor 2, structural size and ped shape in horizon 2 and percentage of gravel and cobble content, also in horizon 2, were related, but the two pairs of variables are inversely related to each other. This supports the positioning at the extremes of spatial structure developed by ordination (table 2). The only variables not exhibiting good covariate relationships were chroma and pH of the second horizon and chroma, percentage gravel, percentage cobble, and pH of the third horizon.

Table 2—Comparison of first axis ordination selection of coarse-textured parent material soil characteristics by polar ordination (PO), centered principal components analysis (PCA), two-way species indicator analysis (TWINSPAN), and detrended correspondence analysis (DCA). Data set consisted of 22 variables and $n = 55$. Variable suffix indicates associated horizon number

Axis	PO	PCA	TWINSPAN	DCA
1	Size2	Size2	Shape2	Size2
2	Shape2	Shape2	Size2	Shape2
3	Shape3	Size3	Shape3	Shape3
4	Size3	Shape3	Size3	Size3
5	Depth3	Depth3	Chroma3	Depth3
6	Clay2	Clay2	Chroma2	pH3
7	pH3	Depth2	Value3	Depth2
8	Silt2	Silt2	Depth3	Clay2
9	Depth2	pH3	pH2	Clay3
10	pH2	Silt3	Clay2	pH2
11	Silt3	Clay3	Value2	Silt3
12	Clay3	pH2	Depth2	Silt2
13	Value3	Value2	pH3	Value2
14	Value2	Value3	Clay3	Value3
15	%Stone2	Chroma3	Silt3	Chroma3
16	Chroma3	%Cobble3	Silt2	%Cobble3
17	Chroma2	%Gravel3	%Stone3	Chroma2
18	%Cobble3	Chroma2	%Stone2	%Gravel3
19	%Stone3	%Cobble2	%Cobble2	%Stone2
20	%Cobble2	%Stone2	%Cobble3	%Cobble2
21	%Gravel3	%Stone3	%Gravel3	%Stone3
22	%Gravel2	%Gravel2	%Gravel2	%Gravel2

Stepwise discriminant analysis (Dixon 1981) computes classification functions for subsets of quantitative variables by means of F values from an analysis of covariance. Table 3 lists the stratification combinations and selected variables for which F values were significant at the 0.90 level or greater. Through this analysis, 14 variables were identified as containing useful information for discriminating between various stratifications of the data. These variables were:

Chroma2	Clay2	Size3	Shape3	%Cobble3
Size2	%Cobble2	Depth3	Silt3	pH3
Shape2	pH2	Value3	%Gravel3	

Canonical discriminant analysis of the coarse-textured parent material samples stratified into six habitat types resulted in the first three canonical components having F values significant at the 90 percent probability level or greater. All 22 variables had positive or negative correlation values greater than 0.5 within the first three canonical components. This is not surprising because factor analysis showed all variables, but five, were members of highly related covariate groups. By selecting the two largest positive and negative values within each of the three canonical components, six pairs of soil variables were identified as being good discriminators for habitat types.

Positive canonical coefficient pairs:
Value3 – Chroma2 %Gravel2 – %Gravel3
pH3 - Shape3

Negative canonical coefficient pairs:
Depth3 – %Cobble3 Clay2 – Silt2
Shape2 – Size2

Calculations similar to those of stepwise discriminant analysis were produced by canonical discriminant analysis for each of the 11 other data stratifications. Due to redundancy of results, these analyses are not presented. Based on the results of principal component analysis, factor analysis, and stepwise and canonical discriminant analysis, the following four variables were chosen for use in developing discriminant functions: Size2, Size3, %Cobble2, and %Cobble3.

Discriminant functions are the most valuable when analyzing homogeneous groups in which clusters of samples overlap (Sneath and Sokal 1973). This appears to be the situation among habitat types and soils. Statistical significance can only be ascribed to discriminant functions if the variables are multivariate normal, the variance-covariance matrices are similar, prior probabilities are identifiable, and the relationships between variables are linear (Greig-Smith 1983; Pielou 1977; Williams

Table 3—Variables selected, significant *F* value, and degrees of freedom (numerator and denominator) produced by stepwise discriminant analysis on coarse-textured parent material data

Stratification of data	Variable	*F* Value Sig. >0.90	Degrees of freedom	
			Numerator	Denominator
Six habitat types	Size3	6.522	5	49
	%Gravel3	3.277	5	48
	pH3	2.902	5	47
	Size2	3.157	5	46
	%Cobble2	2.575	5	45
Overstory series ABGR-THPL-TSHE	pH2	5.421	2	52
Two overstory series ABGR - TSHE	pH2	9.008	1	41
	Value3	4.447	1	40
	Silt3	6.218	1	39
Understory unions CLUN - ASCA	Size3	16.187	1	53
	Chroma2	7.083	1	52
	%Cobble3	4.589	1	51
ABGR/CLUN - ABGR/ASCA	%Gravel3	5.108	1	16
	%Cobble3	6.765	1	15
	Chroma2	7.411	1	14
	Shape3	4.973	1	13
TSHE/CLUN - TSHE/ASCA	Size3	27.547	1	22
	%Cobble3	8.557	1	21
ABGR/CLUN - ABGR/ASCA - TSHE/CLUN - TSHE/ASCA	Size3	13.315	3	39
	%Gravel3	5.534	3	38
	Value3	4.341	3	3
	pH3	3.401	3	36
	Depth3	3.841	3	35
ABGR/CLUN - TSHE/CLUN	pH2	6.429	1	12
	Clay2	10.740	1	13
	Size3	15.882	1	12
	Shape3	11.155	1	11
ABGR/ASCA - TSHE/ASCA	Size2	15.228	1	25
	%Gravel3	6.665	1	24
	Shape2	6.951	1	23
THPL/CLUN - THPL/ASCA - TSHE/CLUN - TSHE/ASCA	Size3	5.787	3	32
	%Cobble2	5.693	3	31

1983). All four of these assumptions were violated to some extent in these analyses, leaving exploratory generalizations about both the data structure and discriminant functions as the result, rather than statistically significant conclusions.

Using four soil characteristics as variables, the probability of correct classification is equal to or greater than 57 percent for the *Abies grandis* and *Tsuga heterophylla* series habitat types, with 33 percent or less accuracy for *Thuja plicata* habitat types (table 4). The probability of simply guessing the correct habitat type is 16.7 percent. Considering the small sample size and the large amount of unexplained variation indicated by principal component analysis, this degree of classification accuracy is quite good. Although it is somewhat circular to test results with data used to develop the classification scheme, it does act as an acceptable initial test of classification accuracy.

In an attempt to increase the sample size per group and reduce apparent variation, the data set was stratified by overstory climax species (that is, *Abies grandis, Thuja plicata, Tsuga heterophylla*). Table 5 presents the classification results of discriminant analysis for the three series groups using the same four variables as above. The probability of properly assigning a sample to the *A. grandis* or *T. heterophylla* series using the discriminant functions developed is roughly twice the probability of guessing (33.3 percent), whereas for *T. plicata* it is one-half. Possible reasons for the poor accuracy in *T. plicata*

Table 4—Results of classifying six habitat types by four soil characteristics (Size2, Size3, %Cobble2, %Cobble3) using discriminant analysis. Probability of guessing correct classification group is 16.7 percent

Habitat type -Phase	Sample size	Predicted group membership					
		ABGR/CLUN -CLUN	ABGR/ASCA -ASCA	THPL/CLUN -CLUN	THPL/ASCA -ASCA	TSHE/CLUN -CLUN	TSHE/ASCA -ASCA
		Percent					
ABGR/CLUN -CLUN	7	57.1	0	0	0	28.6	14.6
ABGR/ASCA -ASCA	12	16.7	66.7	0	8.3	0	8.3
THPL/CLUN -CLUN	6	0	16.7	16.7	0	33.3	33.3
THPL/ASCA -ASCA	6	33.3	0	0	3.3	16.7	16.7
TSHE/CLUN -CLUN	9	11.1	11.1	0	0	77.8	0
TSHE/ASCA	15	0	13.3	0	0	0	86.7

Table 5—Results of classifying three overstory series by four soil characteristics using discriminant analysis

Sample series	Group size	Predicted group membership		
		ABGR	THPL	TSHE
		Percent		
ABGR	19	63.2	5.3	31.5
THPL	12	33.3	16.7	50.0
TSHE	24	33.3	0	66.7

Table 6—Results of classifying two understory unions by four soil characteristics using discriminant analysis

Sample union	Group size	Predicted group membership	
		CLUN	ASCA
		Percent	
CLUN	22	77.3	22.7
ASCA	33	18.2	81.8

classification may be that a different set of variables is required as discriminators for this climax tree species, or there simply is too much noise (for example, small data set) in this midground portion of what appears to be a relatively narrow environmental continuum. This problem also occurred in the stepwise discriminant analysis (table 3), wherein no significant variables could be found for habitat type groupings of *T. plicata* by itself or when combined with samples from the *A. grandis* series.

A much greater accuracy of classification is achieved by stratifying the data based on two understory unions of *Clintonia uniflora* (Schult.) Kunth. and *Asarum caudatum* Lindl. Table 6 presents the results of this discriminant classification showing approximately 77 percent and 82 percent proper classification, respectively. Stratification of the data into subsets of a single overstory species and two different understory unions should further increase classification accuracy.

The analysis conducted with only 55 samples may have produced results that reflect a simple random structure in the data set. If so, statisticians refer to this model as "overfitting the data" and not a true response to the system being modeled. Therefore, stratification of these data beyond the present level precludes further meaningful analysis.

Tables 7, 8, and 9 present the discriminant score formulas produced for classification of unknown samples into one of six habitat types, one of three overstory climax series, or one of two understory unions. Appendix B defines values for field quantification of structural ped size and percentage of cobbles.

Using four soil characteristics, the formulas calculate a discriminant score for each vegetation unit within a stratification group. The formula that produces the highest discriminating score (DS) has the highest probability of being classified correctly. As an example, one of the original sample plots, assigned by vegetation analysis to the ABGR/CLUN-CLUN habitat type, has the following values for the four discriminating soil characteristics:

Size2	=	4	%Cobble2	=	10
Size3	=	4	%Cobble3	=	20

Table 7—Discriminant score formulas for six habitat types and phases and four soil characteristics

Habitat type -phase	Formula
ABGR/CLUN -CLUN	DS = (17.3 Size2 + 15.0 Size3 + 4.5 Cobble2 – 0.01 Cobble3 + 227.9)
ABGR/ASCA -ASCA	DS = (18.4 Size2 + 12.6 Size3 + 4.4 Cobble2 + 0.01 Cobble3 + 231.6)
THPL/CLUN -CLUN	DS = (16.9 Size2 + 13.1 Size3 + 4.3 Cobble2 + 0.04 Cobble3 + 233.7)
THPL/ASCA -ASCA	DS = (17.3 Size2 + 13.9 Size3 + 4.6 Cobble2 – 0.01 Cobble3 + 230.3)
TSHE/CLUN -CLUN	DS = (18.0 Size2 + 14.0 Size3 + 4.5 Cobble2 – 0.06 Cobble3 + 229.8)
TSHE/ASCA -ASCA	DS = (15.9 Size2 + 12.5 Size3 + 4.1 Cobble2 + 0.12 Cobble3 + 236.6)

Table 8—Discriminant score formulas for three overstory series and four soil characteristics

Overstory series	Formula
ABGR	DS = (13.7 Size2 + 7.4 Size3 + 2.9 Cobble2 + 0.56 Cobble3 + 179.3)
THPL	DS = (13.0 Size2 + 7.5 Size3 + 2.9 Cobble2 + 0.56 Cobble3 + 180.4)
TSHE	DS = (12.7 Size2 + 7.3 Size3 + 2.8 Cobble2 + 0.57 Cobble3 + 182.3)

Table 9—Discriminant score formulas for the modal phase of two understory unions and four soil characteristics

Understory union	Formula
CLUN	DS = (10.6 Size2 + 9.2 Size3 + 2.6 Cobble2 + 0.52 Cobble3 + 166.6)
ASCA	DS = (10.5 Size2 + 8.2 Size3 + 2.5 Cobble2 + 0.57 Cobble3 + 168.7)

Using the six formulas in table 7, the discriminant scores (DS) calculated for each of the six habitat types are:

ABGR/CLUN-CLUN	DS = 401.9
ABGR/ASCA-ASCA	DS = 399.8
THPL/CLUN-CLUN	DS = 397.5
THPL/ASCA-ASCA	DS = 400.9
TSHE/CLUN-CLUN	DS = 401.6
TSHE/ASCA-ASCA	DS = 393.6

The highest discriminant score, calculated by the ABGR/CLUN-CLUN formula is 401.9, indicating this is the best choice for classification based on four soil characteristics. Table 4 shows a 57 percent probability that this is a correct classification. A rank order of scores can be used to identify other potential habitat types for consideration as classified units. In the example, the second best habitat type choice would be TSHE/CLUN-CLUN. With highly similar sites, classification errors can occur due to rounding of significant numbers in the formula. In all cases where discriminating scores are within three-tenths equivalent values (such as 401.9 vs. 401.6), further supporting evidence from investigation of onsite or adjacent vegetation is required for accurate classification.

Ecological Interpretations

Even though soil-vegetation relationships were identified, the ecological interpretations are extremely hypothetical. The habitat types used to define the study environment are positioned along a continuous moisture-temperature gradient. *Tsuga heterophylla* can maintain viable populations only in the most moderate moisture and temperature regimes found in northern Idaho. Sites adjacent to *T. heterophylla*, but either too dry, too wet, too hot, or too cold for it to successfully reproduce are generally dominated by *Thuja plicata*. The harshest environments within this continuum, sites too hot and dry or too cold for *T. plicata*, are dominated by *Abies grandis*. The two understory unions likewise respond to environmental gradients, which generally can be described as warm-moist sites supporting both climax *Asarum caudatum* and *Clintonia uniflora*, while the colder and/or drier sites support only *C. uniflora*. Within the theorized functions for soil (Jenny 1941) and vegetation properties (Major 1951), these environmental relations are incorporated in the climate, relief, and parent material factors. If a change in vegetation is related to changing environmental factors, then a concurrent, but not necessarily convergent, shift in soil properties should occur.

Within the data used for this study no statistically or ecologically significant correlation could be found between habitat types and taxonomic soil units. Reasons for this failure are probably related to: the restricted amount of available data and its nonconformity to statistical constraints; the relatively narrow environmental gradient encompassed by the habitat types studied; and the broad geographic region included within the data base.

Interpretation of ecological relationships between habitat types and soil characteristics appears to be related directly to and confounded by climatic conditions that control soil genesis and species composition of the plant community. The cooler and wetter climatic regimes affecting northern Idaho are so recent (Mehringer 1985) that most of the vegetation-soil ecosystems are still in a state of flux. Primary successional development of plant communities and soil horizonation are proceeding at different rates. Duchaufour (1982) refers to short-cycle and long-cycle patterns of soil formation, with the dominant functional factors being vegetation and climate, respectively. The vegetation of northern Idaho has responded rapidly to the climatic change, whereas the soils are immature relative to the current conditions of climate and vegetation. This could account for the high variance values for soil characteristics when viewed from the perspective of a narrow vegetational continuum. I hypothesize that the habitat types used in this study are relatively stable in composition given the current climate, but the soils associated with these habitat types have not yet stabilized.

CONCLUSIONS

For the geographic area studied, there appear to be no universal soil variables or sets of variables that can be used to predict the climax plant communities. The relationships between vegetation and soils are multifactorial and dynamic; the effect upon plant growth or reproduction of any one soil variable changes quantitatively and/or qualitatively with every variation in the complex of environmental factors. Yet, identifiable relationships do exist between a stratified set of soils and vegetation. This study was able to identify soil characteristics usable for differentiating pairs or groups of habitat types occurring on specific groupings of parent materials in northern Idaho. The concepts explored herein should be widely useful. But they should be applied only to northern Idaho ecosystems; only to the typal phase of the six habitat types discussed; and only to soils developed from the group of coarse-textured parent materials previously defined.

The importance of these findings for forest managers is twofold. First, with a large sample size and sufficient insight, a unique set of soils can be correlated with individual habitat types. Within a habitat type each set of functional soil-forming factors will develop a soil specific to that set of environmental conditions. Second, and probably more important, a silvicultural prescription may not produce a uniform vegetational response when applied to a specific habitat type or habitat type-phase occupying more than one type of soil. The use of universal guidelines for prescribed silvicultural treatments, site preparation, selection of regeneration species, stocking levels, and many other management activities has often resulted in failure. Many of these failures were the result of an inappropriate prescription chosen because of insufficient knowledge about these highly complex ecosystems. Effective management requires an individualistic prescription for each stand based on knowledge of its unique features, particularly its soils.

REFERENCES

Barnes, B. V.; Pregitzer, K. S.; Spies, T. A.; Spooner, V. H. 1982. Ecological forest site classification. Journal of Forestry. 80: 493-498.

Base, S. R.; Fosberg, M. A. 1971. Soil-woodland correlation in northern Idaho. Northwest Science. 45: 1-6.

Bray, J. R.; Curtis, J. T. 1957. An ordination of the upland forest communities of southern Wisconsin. Ecological Monographs. 27: 325-349.

Buol, S. W.; Hole, F. D.; McCracken, R. J. 1980. Soil genesis and classification. 2d ed. Ames, IA: Iowa State University Press. 404 p.

Bunting, S. C. 1978. The vegetation of the Guadalupe Mountains. Lubbock, TX: Texas Tech University. 183 p. Dissertation.

Cooper, S. V.; Neiman, K. E.; Steele, R.; Roberts, D. W. 1987. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. INT-236. Ogden UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 135 p.

Daubenmire, R. 1956. Climate as a determinant of vegetation distribution in eastern Washington and northern Idaho. Ecological Monographs. 26: 131-154.

Daubenmire, R. 1968. Plant communities: a textbook of plant synecology. New York: Harper Row. 300 p.

Daubenmire, R. 1970. Steppe vegetation of Washington. Tech. Bull. 62. Pullman, WA: Washington State Agricultural Experiment Station. 131 p.

Daubenmire, R.; Daubenmire, J. 1968. Forest vegetation of eastern Washington and northern Idaho. Tech. Bull. 60. Pullman, WA: Washington State Agricultural Experiment Station. 104 p.

Dixon, W. J. 1981. BMDP statistical software. Berkeley, CA: University of California Press. 726 p.

Duchaufour, P. 1982. Pedology: pedogenesis and classification. (Translated by T. R. Paton.) London: George Allen and Unwin. 448 p.

Fosberg, M. A.; Falen, A. L. 1983. Guide for preparing soil pedon description: abbreviations, descriptions and classifications. Moscow, ID : University of Idaho, Department of Plant and Soil Science. 107 p.

Gauch, H. G. 1977. ORDIFLEX – a flexible computer program for four ordination techniques: weighted averages, polar ordination, principal components analysis, and reciprocal averaging, release B. Ithaca, NY: Cornell University. 185 p.

Gauch, H. G. 1982. Multivariate analysis in community ecology. Cambridge, England: Cambridge University Press. 298 p.

Greig-Smith, P. 1983. Quantitative plant ecology. 3d ed. Studies in Ecology. Vol. 9. Berkeley, CA : University of California. 359 p.

Hall, F. C. 1973. Plant communities of the Blue Mountains in eastern Oregon and southwestern Washington. R-6 Area Guide 3-1. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 62 p.

Hann, W. J. 1982. A taxonomy for classification of seral vegetation of selected habitat types in western Montana. Moscow, ID: University of Idaho. 235 p. Dissertation.

Hill, M. O. 1979a. DECORANA – a FORTRAN program for detrended correspondence analysis and reciprocal analysis. Ithaca, NY: Cornell University. 52 p

Hill, M.O. 1979b. TWINSPAN – a FORTRAN program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes. Ithaca, NY: Cornell University. 90 p

Hironaka, M.; Fosberg, M. A.; Winward, A. H. 1983. Sagebrush-grass habitat types of southern Idaho. Bull. 35. Moscow, ID: University of Idaho, Forestry, Wildlife, and Range Experiment Station. 44 p.

Hitchcock, C. L.; Cronquist, A. 1973. Flora of the Pacific Northwest. Seattle, WA: University of Washington Press. 730 p.

Jenny, H. 1941. Factors of soil formation. New York: McGraw-Hill. 281 p.

Jenny, H. 1958. Role of the plant factor in the pedogenic functions. Ecology. 39: 5-16.

Jenny, H. 1980. The soil resource: origin and behavior. New York: Springer-Verlag. 377 p.

Johnson, F. D. 1968. Disjunct populations of red alder in Idaho. In: Trappe, J. M.; Franklin, J. F.; Tarrant, R. F.; Hausen, G. M., eds. Proceedings of 40th annual meeting of Northwest Scientific Association; Pullman, WA. Portland, OR: Northwest Scientific Association: 1-8.

Johnson, F. D.; Steele, R. 1978. New plant records from Pacific coastal refugia. Northwest Science. 52: 205-211.

Loucks, O. L. 1962. Ordinating forest communities by means of environmental scalars and phytosociological indices. Ecological Monographs. 32: 137-166.

Major, J. 1951. A functional, factorial approach to plant ecology. Ecology. 32: 392-412.

McCune, B.; Allen. T. F. H. 1985. Will similar forests develop on similar sites? Canadian Journal of Botany. 63: 367-376.

Mehringer, P. J., Jr. 1985. Late-Quaternary pollen records from the interior Pacific Northwest and northern Great Basin of the United States. In: Bryant, V. M., Jr.; Holloway, R. G., eds. Pollen records of late-Quaternary North American sediments. Dallas, TX: American Association of Stratigraphic Paleonologists Foundation: 167-189.

Monserud, R. A.; Moody, U.; Breuer, D. 1986. Soil-site relationships for inland Douglas-fir. Moscow, ID: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Labratory. 43 p. Review draft.

Mueggler, W.; Stewart, W. 1980. Grassland and shrubland habitat types of western Montana. Gen. Tech. Rep. INT-66. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 154 p

Munsell. 1975. Munsell soil color charts. Baltimore, MD: Kollmorgen Corp.

Neiman, K. E. 1986. Soil discriminant functions for six habitat types in northern Idaho. Moscow, ID: University of Idaho. 174 p. Dissertation.

Nimlos, T. J.; Zuuring, H. 1982. The distribution and thickness of volcanic ash in Montana. Northwest Science. 56: 190-198.

Pacific Northwest River Basin Commission. 1969. Climatological handbook. Columbia Basin States. Precipitation. Vol. 2. Vancouver, WA. Pacific Northwest River Basin Commission Meteorological Committee. 262 p.

Pfister, R. D.; Arno, S. F. 1980. Classifying forest habitat types based on potential climax vegetation. Forest Science. 26: 52-70.

Pfister, R.; Kovalchik, B.; Arno, S.; Presby, R. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 174 p.

Pielou, E. C. 1977. Mathematical ecology. 2d ed. New York: John Wiley & Sons. 385 p.

Ross, S. H.; Savage, C. N. 1967. Idaho earth science: geology, fossils, climate, water, and soils. Earth Science Series No. 1. Moscow, ID: Idaho Bureau of Mines and Geology. 271 p.

SAS Institute. 1982a. SAS user's guide: basics. Cary, NC: SAS Institute Inc. 921 p.

SAS Institute. 1982b. SAS user's guide: statistics. Cary, NC: SAS Institute Inc. 584 p.

Sneath, P. H. A.; Sokal, R. R. 1973. Numerical taxonomy: the principles and practice of numerical classification. San Francisco: W. H. Freeman and Co. 573 p.

Sondheim, M. W.; Klinka, K. 1983. The relationship of soil and physiographic attributes to an ecological classification system. Canadian Journal of Soil Science. 63: 97-112.

Steele, R. 1971. Red alder habitats in Clearwater County, Idaho. Moscow, ID: University of Idaho. 88 p. Thesis.

Steele, R.; Pfister, R. D.; Ryker, R. A.; Kittams, J. A. 1981. Forest habitat types of central Idaho. Gen. Tech. Rep. INT-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 138 p.

Steele, R.; Cooper, S. V.; Ondov, D. W.; Roberts, D. W.; Pfister, R. D. 1983. Forest habitat types of eastern Idaho - western Wyoming. Gen. Tech. Rep. INT-144. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment. 122 p.

Thornbury, W. D. 1965. Regional geomorphology of the United States. New York: John Wiley and Sons. 609 p.

Tisdale, E. W. 1979. A preliminary classification of Snake River Canyon grasslands in Idaho. Station Note 32. Moscow, ID: University of Idaho, Forest, Wildlife and Range Experiment Station. 8 p

Tisdale, E. W.; Bramble-Brodahl, M. 1983. Relationships of site characteristics to vegetation in canyon grasslands of west central Idaho and adjacent areas. Journal of Range Management. 36: 775-778.

U.S. Department of Agriculture, Soil Conservation Service. 1972. Guides for calculating available water capacity. Tech. Notes No. 2. Boise, ID. 3 p.

U.S. Department of Agriculture, Soil Conservation Service. 1975. Soil taxonomy. Agric. Handb. 436. Washington, DC. 754 p.

U. S. Department of Agriculture, Soil Conservation Service, Soil Survey Staff. 1981. Preliminary soil survey manual. 430-V-55M. Washington, DC.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration. 1985. Climatological data. Annual summary. Vol. 88, No. 13. Idaho. Washington DC: National Oceanic and Atmospheric Administration.

Williams, B. K. 1983. Some observations on the use of discriminant analysis in ecology. Ecology. 64: 1283-1291.

Williams, W. T.; Lambert, J. M. 1961. Multivariate methods in plant ecology: III. Inverse association analysis. Journal of Ecology. 49: 717-730.

APPENDIX A: SOILS CLASSIFIED TO FAMILY LEVEL BASED ON PHYSICAL DATA. INCLUDES HABITAT TYPES ASSOCIATED WITH FAMILY AND PLOT NUMBER OF SAMPLE CLASSIFIED TO THAT FAMILY

Great Group	Subgroup	Family	Habitat type	Plot No.
Eutroboralf	Typic	fine, mixed, frigid	TSHE/CLUN	92141
		fine-loamy, mixed, frigid	THPL/ASCA	92130
Glossoboralf	Eutric	fine-loamy, mixed	ABGR/CLUN	93110
		loamy, skeletal, mixed	TSHE/CLUN	93131
			TSHE/ASCA	93136
			TSHE/ASCA	94009
			TSHE/ASCA	94038
Udifluvent	Typic	sandy, mixed, frigid	TSHE/ASCA	92161
Udipsamment	Typic	sandy, mixed, frigid	TSHE/ASCA	92158
Udorthent	Typic	sandy, mixed, frigid	THPL/ASCA	40559
Cryandept	Entic	medial over sandy or sandy skeletal	THPL/ASCA	38503
Cryocrept	Andic	coarse-loamy, mixed	ABGR/CLUN	38314
	Dystric	sandy, mixed	ABGR/ASCA	38308
	Typic	loamy, skeletal, mixed	ABGR/CLUN	38305
			ABGR/CLUN	38555
Cryumbrept	Entic	sandy, skeletal, mixed	ABGR/CLUN	38522
Dystrochrept	Andic	fine loamy, mixed, frigid	ABGR/CLUN	40740
		loamy, skeletal, mixed, frigid	THPL/CLUN	94025
			TSHE/CLUN	92139
			TSHE/ASCA	92113
	Typic	fine-loamy over sandy or sandy-skeletal, mixed, frigid	TSHE/ASCA	93156
		loamy over sandy or sandy-skeletal, mixed, frigid	THPL/CLUN	40560
Dystrochrept	Typic	loamy, skeletal, mixed, frigid	THPL/ASCA	92118
		coarse loamy, mixed, frigid	ABGR/ASCA	40553
			THPL/CLUN	40548
			TSHE/CLUN	92150
		sandy, skeletal, mixed, frigid	ABGR/ASCA	38566
	Umbric	sandy, skeletal, mixed, frigid	ABGR/CLUN	38541
			ABGR/ASCA	38706

(con.)

APPENDIX A. (Con.)

Great Group	Subgroup	Family	Habitat type	Plot No.
Eutrochrept	Typic	sandy, mixed, frigid	ABGR/ASCA	38707
Haplumbrept	Andic	loamy, skeletal, mixed, frigid	ABGR/ASCA	40552
Vitrandept	Typic	loamy, skeletal, mixed, frigid	THPL/ASCA	94011
		medial over loamy, mixed, frigid	TSHE/CLUN	92102
			TSHE/CLUN	92134
		medial over loamy-skeletal, mixed, frigid	ABGR/ASCA	93116
			ABGR/ASCA	94043
			ABGR/ASCA	94047
			THPL/CLUN	93154
			THPL/CLUN	94060
			THPL/ASAC	94029
			TSHE/CLUN	93106
			TSHE/ASCA	93111
			TSHE/ASCA	93115
			TSHE/ASCA	93125
			TSHE/ASCA	93126
			TSHE/ASCA	93129
	Umbric	loamy-skeletal, mixed, frigid	ABGR/ASCA	93160
		medial over loamy-skeletal, mixed, frigid	ABGR/ASCA	94026

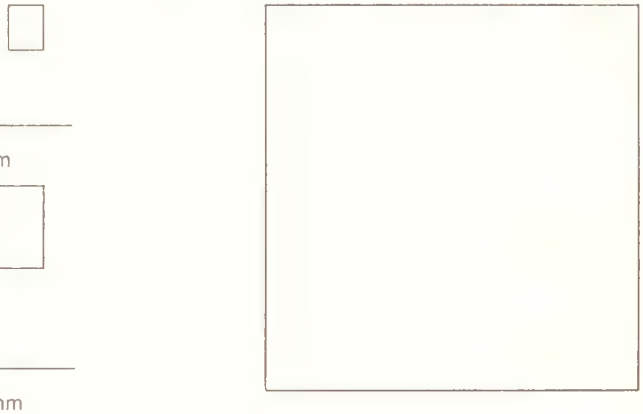
APPENDIX B: DEFINITIONS AND PHYSICAL VALUES FOR FIELD QUANTIFICATION OF %COBBLES AND STRUCTURAL PED SIZE (FROM FOSBERG AND FALEN 1983)

Cobbles – Rock fragments of rounded, subrounded angular or irregular shape. Size range of 7.6 to 25 cm (3 to 10 in) diameter.

%Cobbles – Visual estimate of percent of soil volume occupied by rock fragments of cobble size class.

Structural Ped Size – all ped shapes should be measured by the size classes for angular and sub-angular blocky structure.

Size Class	Diameter
1	<5 mm
2	5 to 10 mm
3	10 to 20 mm
4	20 to 50 mm



Neiman, Kenneth E., Jr. 1988. Soil characteristics as an aid to identifying forest habitat types in Northern Idaho. Res. Pap. INT-390. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

Vegetation and soil physical characteristics were analyzed to identify numerical patterns within the soils data, relationships between soils and habitat types, and soil characteristics related to specific habitat types. Ordination and discriminant analysis techniques were used to identify four soil characteristics useful in identifying soils variation between six highly similar habitat types in northern Idaho. Improved classification techniques will allow for greater accuracy in predicting site capabilities and response of vegetation to disturbance.

KEYWORDS: soil-vegetation relationships, numerical soil taxonomy, multivariate soil-vegetation analysis

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-391

May 1988

Juniper, Pinyon, Oak, and Mesquite Volume Equations for Arizona

David C. Chojnacky

AUG 17 1988
PUBLIC DOCUMENTS

THE AUTHOR

DAVID C. CHOJNACKY is a research forester in the Forest Survey unit, Intermountain Research Station. He holds a B.S. degree in mathematics from the University of Idaho, Moscow, an M.S. degree in watershed management from the University of Arizona, Tucson, and a Ph.D. degree in forest biometry from Colorado State University, Fort Collins. He has been with the Forest Service since 1979. Before coming to Ogden, he worked for the Forest Research Laboratory at Oregon State University, Corvallis.

RESEARCH SUMMARY

Cubic foot volume equations have been developed for Arizona's juniper, pinyon, oak, and mesquite species. Volume predictions can be obtained for wood and bark combined of all stem and branch material 1.5 inches in diameter and larger. The required measurement variables are tree basal diameter near the root collar and total tree height.

The equations were based on data collected on 1,442 trees at 291 field locations throughout Arizona. Data were collected on all woodlands owned or managed by the following: State of Arizona; private individuals and corporations; Papago, Hopi, and Kaibab Indian Reservations; Coronado and Prescott National Forests; all Arizona Bureau of Land Management Districts; and several other public entities.

Results are presented in equation and tabular formats. Volume equation construction and equation reliability are discussed. Graphs display results compared to those from other available Arizona woodland volume studies.

ACKNOWLEDGMENTS

Many individuals contributed to the 1985 Arizona woodland inventory. They provided the necessary data for volume equation construction. Participants were from the U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management and Bureau of Indian Affairs; and Arizona State Land Department. Special thanks to field crew leaders, Frank Angele, Ali Conner, Roger Conner, Claire Dailey, Larry DeBlander, Valerie Kalve, and Robert Rhoads, from the Intermountain Research Station, who trudged throughout Arizona's woodlands for 10 months to collect the data.

Cover photos: Upper: One-seed juniper above Chino Valley, Prescott National Forest.
Lower: Mesquite across valley from Santa Rita Mountains, Coronado National Forest

Intermountain Research Station
324 24th Street
Ogden, UT 84401

Juniper, Pinyon, Oak, and Mesquite Volume Equations for Arizona

David C. Chojnacky

INTRODUCTION

Arizona supports vast and diverse juniper, pinyon, oak, and mesquite woodland forests. Much of northern Arizona contains juniper-pinyon woodlands. In the central part of the State and on the lower slopes of the southern mountain ranges, an oak-juniper-pinyon woodland thrives. Mesquite woodlands occur between the southern mountain ranges interspersed with Sonoran Desert and grasslands. Arizona's woodlands, by USDA Forest Service definition (USDA FS 1985), have at least 10 percent crown coverage from trees of woodland species.

Recent economic and management needs for information on Arizona's woodlands prompted an extensive inventory in 1985 (USDA FS 1985). Primary objective was to determine total woodland tree volume. Because direct woodland volume measurement is time consuming and costly, data were collected in the inventory on a subsample of trees for later volume equation development. This paper reports on volume equations constructed from that data.

Previous efforts to develop volume equations for pinyon and juniper species revealed that basal diameter, crown dimensions, total height, and number of basal stems are important predictor variables of tree volume (summarized in Chojnacky 1985). Similar results have also been found for oak and mesquite woodland species (Gronski 1987; Pillsbury and Kirkley 1984; Whisenant and Burzlaff 1978).

Juniper, pinyon, and oak volume estimation specific to Arizona was summarized by Barger and Ffolliott (1972). They published volume tables for pinyon, Utah juniper, alligator juniper, and Gambel oak. These were produced by modifying, extending, or adapting work by Howell and Lexen (1939), Howell (1940), and Gevorkiantz and Olsen (1955). These volume tables require total height and basal diameter for pinyon or diameter at breast height for juniper and oak. Since the Barger and Ffolliott summary, several juniper, pinyon, and oak volume equations have been developed for Arizona's Hualapai, Havasupai, Fort Apache, and San Carlos Indian Reservations (Chojnacky and Ott 1986; Chojnacky 1988). These equations predict volume from basal diameter and total height. For Arizona's mesquite, Olson (1940) and Andrews (1988) each constructed volume equations from basal diameter.

Based on past woodland volume work in Arizona and elsewhere, some form of tree diameter measurement and total tree height are the most common volume predictor variables. From previous work (Chojnacky 1985; Chojnacky and Ott 1986), three principles relating the importance of diameter and height to woodland volume prediction seem clear:

1. Volume is adequately predicted from the combination variable, diameter squared times height divided by 1,000 (DSQH).
2. The volume-to-DSQH relationship is linear, except for the largest trees.
3. The volume-to-DSQH relationship differs between single-stem and multiple-stem trees of a given species.

These principles are not surprising, because they follow from well-known mensuration results for many tree species. Because they also reflect past woodland volume results from other studies, additional strategies for volume equation construction were not sought.

DATA COLLECTION

Volume data were collected from 291 plots (fig. 1) owned or managed by the State of Arizona; private individuals or corporations; Papago, Hopi, and Kaibab Indian Reservations; Coronado and Prescott National Forests; all Arizona Bureau of Land Management Districts; and some miscellaneous public entities. The field plots were subsampled from the 1985 Arizona woodland inventory (USDA FS 1985). Plots were proportionately selected

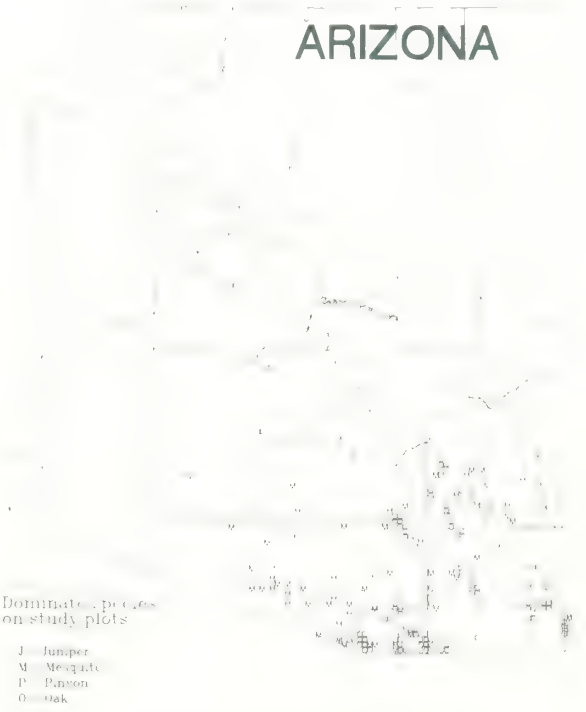


Figure 1—Location map of the 291 study plots.

Table 1—Summary of Arizona woodland volume data by species group

Ownership or management agency	Number of trees	Mean volume	Median volume	Mean DRC	Mean height	Single-stem trees	Number of plots[1]
		Ft^3	Ft^3	Inches	Feet	Percent	
Juniper species group							
Private or corporate	169	7.5	2.4	12.0	12	41	37
Arizona Strip BLM District	91	8.4	2.7	11.4	13	68	20
Coronado National Forest	88	6.5	2.9	11.3	14	58	50
State of Arizona	83	10.7	5.2	13.8	14	43	17
Prescott National Forest	75	6.9	1.6	9.9	13	64	15
Phoenix BLM District	23	3.7	1.3	10.0	10	35	5
Hopi Indian Reservation	11	7.9	5.9	13.8	12	64	4
Kaibab Indian Reservation	5	9.4	6.0	11.6	19	100	1
Total	545	7.8	2.6	11.7	13	52	149
Mesquite species group[2]							
State of Arizona	120	2.9	1.4	8.2	11	35	23
Papago Indian Reservation	67	2.5	1.2	7.0	12	46	16
Coronado National Forest	55	4.2	1.0	8.1	12	55	13
Private or corporate	49	1.8	0.8	7.4	10	39	9
Safford BLM District	19	1.5	1.0	8.0	8	21	5
Other public	6	1.1	.6	5.8	11	50	1
Phoenix BLM District	5	1.4	1.3	5.8	13	40	1
Total	321	2.7	1.2	7.7	11	41	68
Oak species group							
Coronado National Forest	298	3.5	1.8	9.0	12	62	99
Private or corporate	31	7.0	2.6	10.1	16	48	9
Prescott National Forest	10	4.7	3.2	10.0	16	30	4
Safford BLM District	8	1.1	.5	6.6	9	50	2
State of Arizona	2	12.1	12.1	12.4	14	100	1
Other public	1	76.4	76.4	26.6	35	100	1
Total	350	4.0	1.8	9.1	13	60	116
Pinyon species group							
Coronado National Forest	76	2.5	1.3	7.1	13	95	37
Arizona Strip BLM District	32	3.3	1.1	7.2	14	100	14
Private or corporate	32	2.7	1.0	7.0	13	88	12
State of Arizona	31	4.7	1.7	7.8	14	94	9
Prescott National Forest	25	3.2	1.6	6.6	17	100	9
Hopi Indian Reservation	13	1.8	.6	6.8	11	100	4
Phoenix BLM District	9	12.6	2.4	10.1	17	89	4
Safford BLM District	5	.8	.5	5.1	11	100	2
Kaibab Indian Reservation	3	1.6	.2	5.5	13	100	1
Total	226	3.3	1.2	7.2	14	95	92

[1]Because more than one species group occurred on many plots, summation of totals exceeds the total number of study plots.
[2]Includes 12 *Olneya* and 19 *Acacia*.

from map grid points systematically established on all woodlands of the owner or management groups sampled.

Resulting sampling intensities, with two exceptions, were about one plot located every 15 miles across the land base inventoried. The two exceptions, the southern Arizona counties and the Coronado National Forest, were sampled more intensively at about one plot every 10 miles and one plot every 3 miles, respectively. This was done to ensure a large enough sample of mesquite and evergreen oak trees. Sampling intensities were established on maps, and only those plots supporting woodland vegetation were field sampled. Therefore, actual field plots were spaced out much farther than the initial sampling grid because of many nonwoodland inclusions within the land base inventoried. Field plot size was 0.2 acre when crown cover of the surrounding stand was less than 30 percent, and 0.1 acre when crown cover was more than 30 percent. On each plot, about six trees (four for the Coronado) were randomly selected from three diameter classes, 3.0 to 9.9, 10 to 18, and >18 inches diameter at root collar (DRC).

Volume estimation was done using visual segmentation, a nondestructive method of counting the numbers of wood segments within a tree (Born and Chojnacky 1985). Wood segment dimensions were determined by dividing tree stems and branches into 1- to 6-foot length sections using 2-inch diameter classes. Some segment dimensions in

lower portions of trees were measured, but most were estimated by sight. Cubic foot volume was computed for each segment using Huber's log formula (Husch and others 1982, p. 101). For each tree, segments that included wood and bark of all stems and branches larger than 1.5 inches in diameter were summed into a gross cubic foot volume. Both live and dead wood were included.

Other tree variables measured for volume equation development were total height, DRC, and number of basal stems. For trees forking at the root collar, an equivalent diameter (EDRC) was calculated for use in place of DRC:

$$\text{EDRC} = \sqrt{\sum_{i=1}^{n} D_i^2} \qquad (1)$$

where

n = number of basal stems 1.5 inches or larger
D_i = basal diameter of each stem.

Species sampled, followed in parentheses by numbers sampled, were *Juniperus osteosperma* (Torr.) Little (266), *J. monosperma* (Engelm.) Sarg. (169), *J. deppeana* Steud. (95), *J. erythrocarpa* Cory (15), *Pinus edulis* Engelm. (123), *P. cembroides* Zucc. (72), *P. edulis* var. *fallax* Little (31), *Prosopis velutina* Woot. (290), *Acacia greggii* Gray (19), *Olneya tesota* Gray (12), *Quercus emoryi* Torr. (85), *Q. arizonica* Sarg. (37), *Q. hypoleucoides* A. Camus (23), *Q. oblongifolia* Torr. (17), *Q. gambelii* Nutt. (5), and 183 combined *Quercus* hybrids, *Q. turbinella* Greene, *Q. chrysolepis* Liebm., and perhaps a few other evergreen oaks. For initial analysis, species were combined by genus, except for *Prosopis*, *Acacia*, and *Olneya*, which were combined into a mesquite group (table 1).

MODELING

Volume was compared to the combination variable, DRC or EDRC squared times height divided by 1,000 (DSQH), and other data characteristics through graphing. This was done to examine the volume data for differences among species and to examine the volume-to-DSQH relationship.

Little evidence was found to separate the data beyond juniper, oak, pinyon, and mesquite species groups. Either a species was represented by too few trees or species volume variation within a group was similar for all species. Visual volume estimation was considered a possible source of variation masking differences between species. Even though visual volume estimation was shown adequate for constructing volume equations (Born and Chojnacky 1985), no validation checks were available to confirm the reliability of the Arizona data. Some mesquite volume data from Pima and Santa Cruz Counties showed less variation in data estimated by one individual than in data estimated by several field crews combined. This probably suggests that visual volume estimation error should be considered if there is a need to identify precise volume relationships between individual species.

Graphs comparing the volume-to-DSQH relationship for all species groups supported the idea that volume can be adequately predicted from DSQH, even though the model relationship tends to change for larger trees. The graphs also showed the volume relationship differed slightly between single-stem and multiple-stem trees.

The point of change in the volume relationship between small and large trees was identified from graphs. Trees for each species group were ranked from smallest to largest, and the point of change was observed between the 90th and 95th percentile, corresponding to DSQH values of 6, 4, 3, and 2 for juniper, oak, pinyon, and mesquite, respectively.

An analysis of variance to test for differences within species groups was done to compare data from northern Arizona counties with data from southern Arizona counties (Chojnacky 1985, p. 5; Graybill 1976, p. 247). All four species groups showed no significant difference between northern and southern Arizona data (F-test significance levels were 0.19 or greater).

Based on the results of the graphical analysis and analysis of variance, volume equations were constructed for seven categories:

1. Single-stem juniper
2. Multiple-stem juniper
3. Single-stem oak
4. Multiple-stem oak
5. Single-stem mesquite
6. Multiple-stem mesquite
7. Single-stem pinyon (with 11 multiple-stem trees included).

The model was broken into two parts to allow for differences between the largest trees and the rest:

$$V = \begin{cases} \beta_0 + \beta_1 X + \beta_2 X^2 & \text{for } X < X_0 \\ \beta_3 + \beta_1 X + \beta_4 / X & \text{for } X > X_0 \end{cases} \qquad (2)$$

where

V = gross cubic foot volume of wood and bark from all stems and branches larger than 1.5 inches in diameter

X = DRC or EDRC squared times height divided by 1,000

β_i = parameters estimated from data

$$X_0 = \begin{cases} 6 \text{ for juniper} & \text{(roughly a 20-inch DRC)} \\ 4 \text{ for oak} & \text{(roughly a 16-inch DRC)} \\ 3 \text{ for pinyon} & \text{(roughly a 12-inch DRC)} \\ 2 \text{ for mesquite} & \text{(roughly a 12-inch DRC)} \end{cases}$$

The two-part volume model was conditioned to be both smooth and continuous at the point where the two equations meet. This was done by imposing two restrictions on the model:

$$\beta_3 = \beta_0 + 3\beta_2 X_0^2 \qquad (3)$$

$$\beta_4 = -2\beta_2 X_0^3 \qquad (4)$$

The restrictions were obtained by equating the two parts of equation 2 for X equal to X_0, and by equating the first derivative of the two parts of equation 2 at the point X equal to X_0. Parameters for the two-part model (eq. 2) were determined using weighted regression with DSQH

raised to the –1.5 power as the weight (Schreuder and Anderson 1984).

Several steps were used to obtain final volume model parameters. After the first regression, Cook's-D influence statistics (Cook 1977) were examined. Using criteria suggested by Belsley and others (1980, p. 29), Cook's-D values corresponding to each tree's volume were arrayed by species group. Trees above gaps in the upper tails of the distributions were identified. Further examination of these data showed inconsistencies in visual volume segmentation application for about half the cases, suggesting some data should be deleted.

Additional parameter estimates were then obtained after deleting data exceeding a given Cook's-D value. After several comparison trials, a Cook's-D value of 0.10 was chosen as a reasonable cut-off point, resulting in deletion of 20 trees. Reducing the Cook's-D cut-off point below 0.10, and deleting more trees, had a diminishing effect on parameter estimation. Final model parameters and tabulated volume predictions are given in the appendix in tables 3, 4, 5, and 6.

MODEL RELIABILITY

Results of regression goodness-of-fit analyses are summarized in table 2. The coefficient of determination (R^2) was computed using the regression weights and computed again without regression weights. Neither computation method was completely satisfactory because the weighted R^2 was based on a rescaled sum of squares that cannot be scaled back to the original data, and the unweighted R^2 was based on a sum of squares that violates the homogeneous variance assumption of least squares regression. But for those who subscribe to R^2-values, those in table 2 show a reasonable data fit to the model.

Confidence intervals, another method to assess goodness-of-fit, were examined. For each volume equation, confidence intervals were computed for two DRC classes corresponding to trees above and below the point of change (X_0). The median size tree was selected in each DRC class for actual computation. Then 95 percent confidence intervals were computed for predicting mean tree volume from varying numbers of sample trees. For example, if five multiple-stem junipers about 9 inches DRC (see first line of table 2) were measured for volume prediction, the expected true volume would lie in an interval ±36 percent of 2.5 ft^3 (1.6 to 3.4 ft^3). If 10 junipers of 9 inches DRC were sampled, the expected true volume would lie in a smaller interval of ±26 percent of 2.5 ft^3 (1.9 to 3.2 ft^3). A sample size of 20 junipers would further reduce the confidence intervals to 19 percent of 2.5 ft^3 (2.0 to 3.0 ft^3). Even larger sample sizes resulted in still smaller confidence intervals, but the interval reduction in relation to sample size diminished with the larger sample sizes.

The confidence intervals were computed as follows:

$$CI = 1.96 \sqrt{MSE\,(1/WT/n + H)} \qquad (5)$$

where

CI = 95 percent confidence interval for a predicted mean

Table 2—Regression statistics from volume modeling

Species group	DRC class	Basal stems	Number of trees	R^2		Predicted volume	Median statistics[1]					
				Weighted[3]	Unweighted[4]		Median DRC	95 percent mean CI[2]				
								n=5	n=10	n=20	n=50	n=100
	Inches					*Ft^3*	*Inches*	*Percent*				
Juniper	<20	Multiple	203	0.91	0.82	2.5	9	36	26	19	13	10
	>20	Multiple	56	.91	.79	27.6	26	16	12	8	5	4
	<20	Single	262	.92	.88	1.4	6	34	25	18	13	11
	>20	Single	24	.92	.81	28.1	20	12	9	6	4	3
Pinyon	<12	Single	203	.89	.82	.9	7	39	30	23	19	17
	>12	Single	23	.89	.96	12.1	13	16	12	8	6	4
Oak	<16	Multiple	130	.91	87	2.3	10	27	20	15	11	9
	>16	Multiple	9	.91	.77	11.9	18	15	11	8	6	4
	<16	Single	193	.90	.82	1.4	7	35	26	20	15	13
	>16	Single	18	.90	89	21.7	19	14	10	7	5	4
Mesquite	<12	Multiple	168	86	.81	1.3	8	38	28	21	16	14
	>12	Multiple	22	.86	.89	9.7	14	18	13	9	6	5
	<12	Single	123	89	.88	.5	5	48	39	34	30	29
	>12	Single	8	.89	.92	11.6	14	13	9	7	6	5

[1]Statistics based on the median of the DRC class.
[2]Confidence intervals (CI) for mean predicted volume for several sample sizes for the median level of DSQH (roughly median DRC) in each DRC class. CI's are expressed as a percentage of predicted volume for each DRC class.
[3]Computed from weighted regression sum of squares with all tree sizes combined.
[4]Recomputed from data without consideration of regression weights.

MSE = mean squared error from weighted regression

WT = regression weight (DSQH raised to the –1.5 power)

n = desired number trees for confidence interval computations

H = leverage or $x_j(X'X)^{-1}x'_j$ as computed by SAS (1985, p. 663) for weighted regression.

DISCUSSION

All equations were compared graphically (fig. 2) for similarities and differences. The multiple-stem equations showed less volume for given DSQH values than did single-stem counterparts for all species groups. Of all the equations, single-stem mesquite appeared most different. However, extrapolation error may be the main cause, because few mesquite trees in the data exceeded a DSQH of 2.

Volume equations from this study (labeled Arizona) were then compared to equations from Hualapai/Havasupai (labeled H & H) and Fort Apache/San Carlos (labeled Apache) Indian Reservations (Chojnacky 1988; Chojnacky and Ott 1986). Also compared were Olson's (1940) and Andrew's (1988) mesquite equations and volume tables given by Barger and Ffolliott (1972, tables 30, 31, and 32).

The Barger and Ffolliott tables required "smoothing" of the tabulated data for graphic comparison. A spline interpolation (SAS 1985, p. 70) was used to plot tabulated data for Utah juniper (labeled B & F JUOS), alligator juniper (labeled B & F JUDE), pinyon (labeled B & F), and oak (labeled B & F).

Because some of the Barger and Ffolliott tables were based on diameter at breast height (d.b.h.), compatible graphic comparison required a conversion equation relating DRC to d.b.h. Data from single-stem trees measured on the San Carlos Indian Reservation (Chojnacky 1988) were used to develop the following equations:

$$\text{Juniper: } DRC = 2.62 + 0.8314\,(d.b.h.) + 0.0135\,(d.b.h.^2) \quad (6)$$
$$n = 78,\ R^2 = 0.96$$

$$\text{Pinyon: } DRC = 1.04 + 1.1181\,(d.b.h.) - 0.0029\,(d.b.h.^2) \quad (7)$$
$$n = 102,\ R^2 = 0.94$$

$$\text{Oak: } DRC = 0.41 + 1.3552\,(d.b.h.) - 0.0122\,(d.b.h.^2) \quad (8)$$
$$n = 76,\ R^2 = 0.92$$

Comparison of the juniper equations for single-stem trees showed large differences between Barger and Ffolliott's (B & F) work and the rest (fig. 3). However, these differences are probably due to volume definition standards. All equations, except Barger and Ffolliott's, included volume of all wood pieces at least 1-foot long and larger than 1.5 inches in diameter. Barger and Ffolliott's definition resulted in less volume per tree by including wood pieces with diameter standards similar to the others but omitting all pieces less than 4 feet long.

The pinyon volume equation from this study (Arizona) was found similar to the Hualapai/Havasupai (H & H) equation (fig. 4). Because Barger and Ffolliott's pinyon volume table appeared to be in error, a modification was made. In their table 31, diameter is defined at stump height for all trees, but it appears the volumes best correspond to d.b.h. for trees smaller than 10 inches and

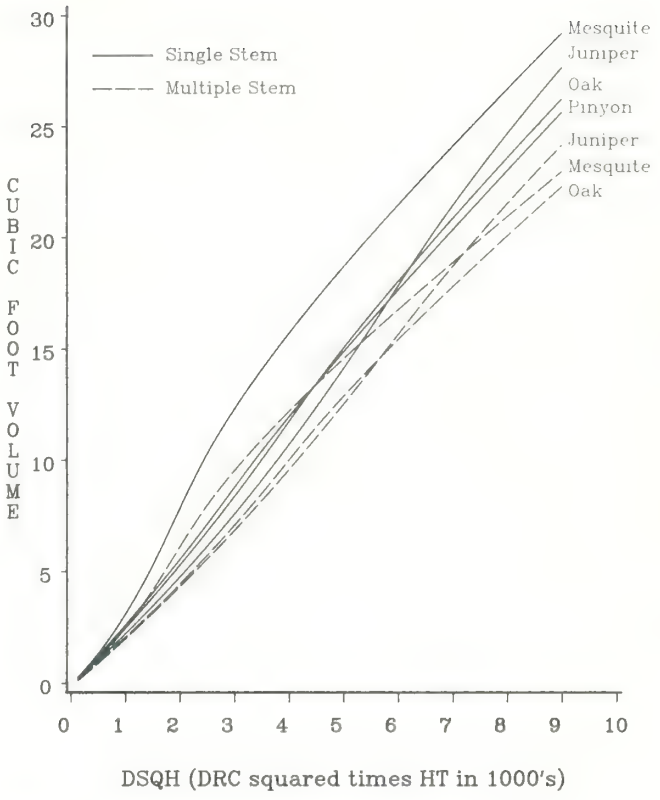


Figure 2—Comparison of the seven woodland volume equations from this study.

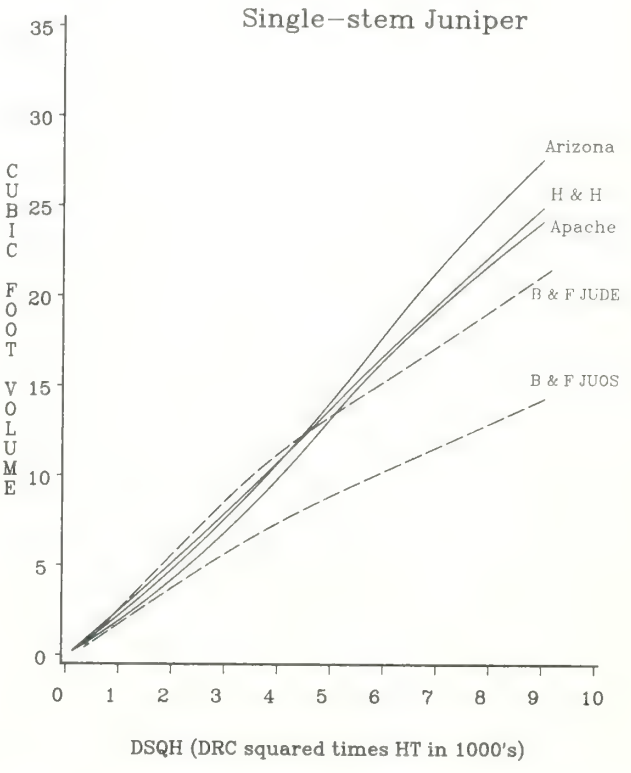


Figure 3—Comparison of this study's single-stem juniper equation (Arizona) with other single-stem juniper equations.

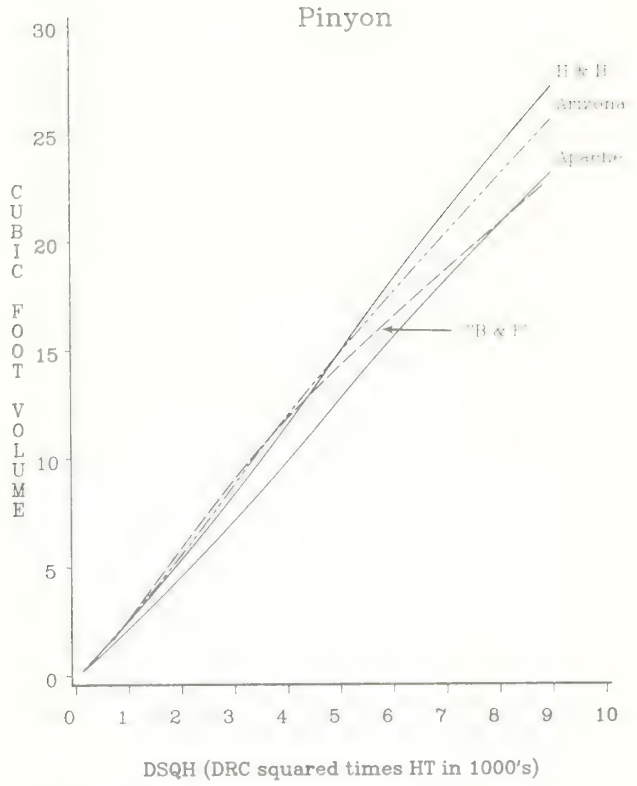


Figure 4—Comparison of this study's pinyon equation (Arizona) with other pinyon equations.

only correspond to diameter at stump height for trees larger than 10 inches. Equation 7 was used to obtain a corrected equation ("B & F" in fig. 4), which appeared comparable to the rest.

Comparison of the oak equations (fig. 5) showed single-stem equations from this study (Arizona) as similar to Fort Apache/San Carlos (Apache) single-stem equations. Apparent low predictions from the Barger and Ffolliott (B & F) equation probably resulted from their volume definition including wood only (the rest included wood and bark) and possibly from excluding branches.

Olson's mesquite equation predicted higher than the others (fig. 6). Perhaps a change in mesquite tree form over the past 45 years accounts for this difference between Olson's 1940 work and the recent single-stem equations. Andrew's equation was almost identical to the Arizona single-stem equation for small and average size trees but differed considerably for larger trees. Because Andrew's work included no large trees with a DSQH larger than 4, extrapolation error is a probable cause for this difference.

Comparison of the available Arizona woodland volume equations clearly showed differences. Those taken from Barger and Ffolliott always appeared to give the lowest volume predictions. In most cases, definition differences explained these discrepancies. Differences between this study's equations and the various Indian reservation equations showed no consistent pattern among the species groups.

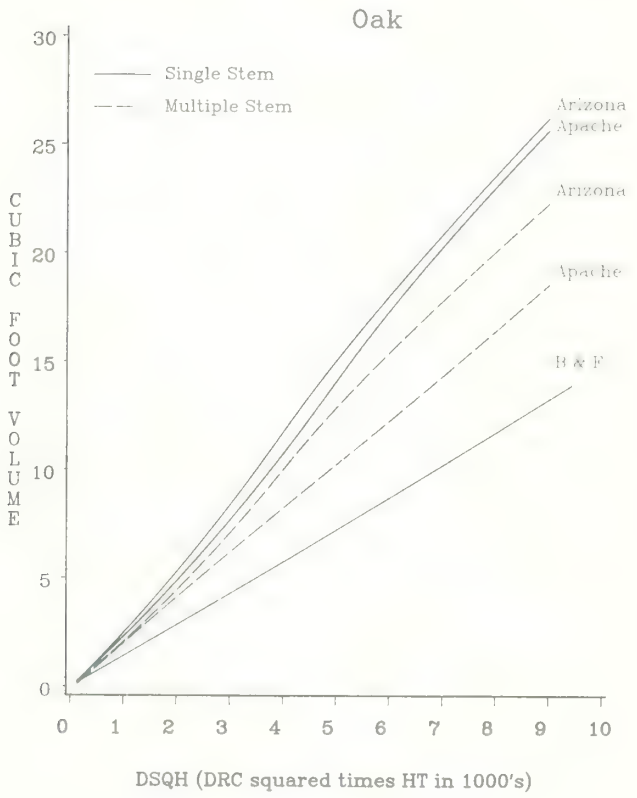


Figure 5—Comparison of this study's oak equation (Arizona) with other oak equations.

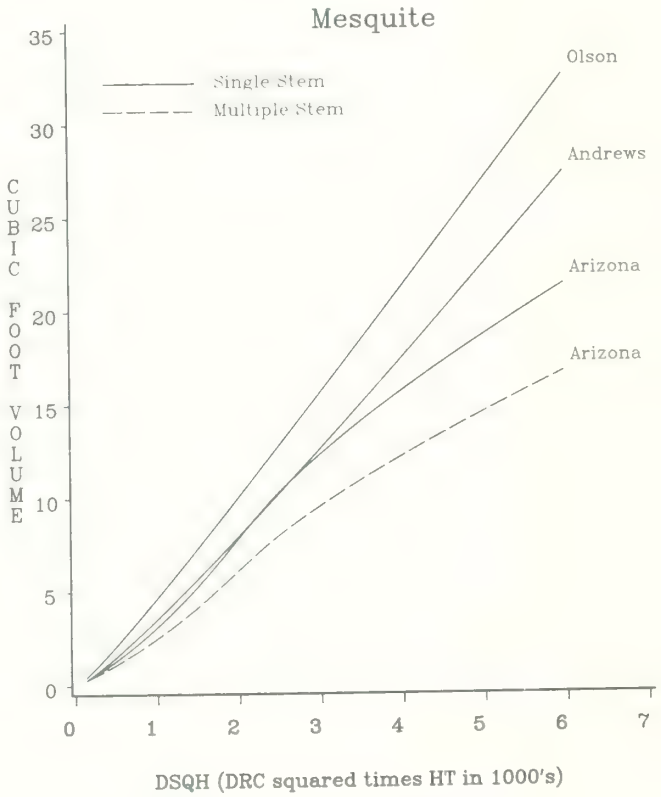


Figure 6—Comparison of this study's mesquite equations (Arizona) with other mesquite equations.

Recommendations on the "best" equations to use are difficult to make. As previously mentioned, definition differences account for some of the equation differences, but the unique developmental data for each equation should also be considered. Potential users should identify their desired volume definition standards and identify their geographic location for application, and then choose the equation that most closely fits their need. Users from the northern Arizona National Forests and from the Navajo Indian Reservation will have the most difficulty selecting equations because no recent woodland volume data have been published for their areas. Some of the 1940's data reported in the Barger and Ffolliott work came from Arizona and New Mexico National Forests, but precise documentation is lacking.

If choosing an appropriate woodland volume equation is an issue, doing visual volume estimation (Born and Chojnacky 1985) on a small sample of test trees (representing species and size diversity from the area of interest) will provide data for making a decision. The volume equation that best predicts the test data then should be used.

REFERENCES

Andrews, S. A. 1988. Volume estimation and multipurpose management of *Prosopis velutina* in Southern Arizona. Tucson, AZ: University of Arizona. 67 p. Thesis.

Barger, R. L.; Ffolliott, P. F. 1972. Physical characteristics and utilization of major woodland tree species in Arizona. Res. Pap. RM-83. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 80 p.

Belsley, D. A.; Kuh, E.; Welsch, R. E. 1980. Regression diagnostics: identifying influential data and sources of collinearity. New York: John Wiley & Sons. 292 p.

Born, J. D.; Chojnacky, D. C. 1985. Woodland tree volume estimation: a visual segmentation technique. Res. Pap. INT-344. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

Chojnacky, D. C. 1985. Pinyon-juniper volume equations for the central Rocky Mountain States. Res. Pap. INT-339. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 27 p.

Chojnacky, D. C. 1988. Woodland volume equations for Arizona Fort Apache and San Carlos Indian Reservations. Res. Note INT-379. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 7 p.

Chojnacky, D. C.; Ott, J. S. 1986. Pinyon-juniper volume equations for Arizona Hualapai and Havasupai Indian Reservations. Res. Note INT-363. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 4 p.

Cook, R. D. 1977. Detection of influential observation in linear regression. Technometrics. 19: 15-18.

Gevorkiantz, S. R.; Olsen, L. P. 1955. Composite volume tables for timber and their application in the Lake States. Tech. Bull. 1104. Washington, DC: U.S. Department of Agriculture, Forest Service. 51 p.

Graybill, F. A. 1976. Theory and application of the linear model. North Scituate, RI: Duxbury Press. 704 p.

Gronski, S. 1987. Mesquite weight/volume estimate table. The Mesquite Messenger. Austin, TX: Los Amigos Del Mesquite. 6(1): 8-9.

Howell, J., Jr. 1940. Pinon and juniper: a preliminary study of volume, growth, and yield. Reg. Bull. 71. Albuquerque, NM: U.S. Department of Agriculture, Soil Conservation Service. 90 p.

Howell, J., Jr.; Lexen, B. R. 1939. Fuelwood volume tables for Rocky Mountain red cedar (*Juniperus scopulorum* Sarg.). Res. Note SW-68. Tucson, AZ: U.S. Department of Agriculture, Forest Service, Southwest Forest and Range Experiment Station. 4 p.

Husch, B.; Miller, C. I.; Beers, T. W. 1982. Forest mensuration. 3d ed. New York: John Wiley & Sons. 402 p.

Olson, C. E. 1940. Mesquite woodlands on southern Arizona Indian Reservations. Reg. Bull. 68. Albuquerque, NM: U.S. Department of Agriculture, Soil Conservation Service. 48 p.

Pillsbury, N. H.; Kirkley, M. L. 1984. Equations for total, wood, and saw-log volume for thirteen California hardwoods. Res. Note PNW-414. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 52 p.

SAS Institute, Inc. 1985. SAS® user's guide: statistics, version 5 edition. Cary, NC: SAS Institute, Inc. 956 p.

SAS Institute, Inc. 1985. SAS/GRAPH® user's guide, version 5 edition. Cary, NC: SAS Instutute, Inc. 596 p.

Schreuder, H. T.; Anderson, J. A. 1984. Variance estimates for volume when D^2H is the covariate in regression. Canadian Journal of Forest Research. 14(6): 818-821.

U.S. Department of Agriculture, Forest Service. 1985. Arizona forest survey field procedures. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forest Survey. 2 parts.

Whisenant, S. G.; Burzlaff, D. F. 1978. Predicting green weight of mesquite (*Prosopis glandulosa* Torr.). Journal of Range Management. 31(5): 396-397.

APPENDIX

This appendix—tables 3 through 6—contains cubic foot volume tables and volume equations for juniper, mesquite, oak, and pinyon trees. Predicted volumes include wood and bark of all stems and branches larger than 1.5 inches outside-bark diameter. Both live and dead material are included. The range of the data is outlined on the tables, and numbers of trees sampled are summarized in the table margins. Use of the equations outside the diameter at root collar (DRC) and height ranges outlined on the tables is not recommended.

Table 3—Juniper outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet) 6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	Number of trees
Inches		*Cubic feet*																
4	Multiple	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7							12
	Single	.2	.2	.3	.4	.4	.5	.6	.7	.7	.8							68
6	Multiple	.3	.5	.6	.8	.9	1.1	1.2	1.4	1.5	1.7							33
	Single	.4	.6	.7	.9	1.1	1.2	1.4	1.6	1.7	1.9							51
8	Multiple	.7	.9	1.2	1.5	1.8	2.1	2.3	2.6	2.9	3.2	3.5	3.8	4.1				28
	Single	.8	1.1	1.4	1.7	2.0	2.3	2.6	2.9	3.2	3.5	3.9	4.2	4.6				37
10	Multiple	1.1	1.6	2.0	2.4	2.9	3.4	3.8	4.3	4.8	5.3	5.8	6.3	6.9				40
	Single	1.3	1.7	2.2	2.7	3.2	3.7	4.2	4.8	5.3	5.9	6.4	7.0	7.6				38
12	Multiple	1.7	2.3	3.0	3.7	4.4	5.1	5.8	6.5	7.3	8.1	8.9	9.7	10.5	11.4	12.6	14.9	29
	Single	1.9	2.6	3.3	4.0	4.8	5.6	6.4	7.2	8.1	9.0	9.9	10.8	11.8	12.8	14.3	16.9	32
14	Multiple	2.4	3.3	4.2	5.2	6.2	7.2	8.3	9.4	10.5	11.6	12.8	14.0	15.3	16.5	18.3	21.1	18
	Single	2.6	3.6	4.7	5.7	6.8	8.0	9.2	10.5	11.8	13.1	14.5	15.9	17.4	18.9	21.0	24.2	17
16	Multiple	3.2	4.4	5.7	7.0	8.4	9.9	11.4	12.9	14.5	16.1	17.7	19.2	20.7	22.0	24.1	27.3	21
	Single	3.5	4.9	6.3	7.8	9.4	11.0	12.8	14.6	16.5	18.4	20.3	22.0	23.7	25.3	27.5	31.1	14
18	Multiple		5.8	7.5	9.3	11.1	13.1	15.1	17.2	19.1	20.9	22.7	24.3	26.0	27.6	29.9	33.7	14
	Single		6.4	8.3	10.4	12.5	14.8	17.2	19.6	21.9	24.0	26.0	27.9	29.7	31.5	34.0	38.1	8
20	Multiple		7.4	9.6	11.9	14.4	16.9	19.3	21.5	23.6	25.7	27.7	29.6	31.5	33.3	36.0	40.5	15
	Single		8.2	10.7	13.4	16.3	19.3	22.1	24.7	27.1	29.4	31.6	33.7	35.7	37.7	40.7	45.5	11
22	Multiple		9.2	12.0	15.0	18.1	20.8	23.4	25.9	28.3	30.6	32.8	35.0	37.2	39.3	42.5	47.7	9
	Single		10.3	13.6	17.1	20.7	23.9	26.8	29.6	32.2	34.7	37.2	39.6	42.0	44.3	47.7	53.2	2
24	Multiple				18.5	21.7	24.7	27.6	30.3	33.0	35.6	38.2	40.7	43.3	45.8	49.5	55.6	13
	Single				21.2	24.9	28.3	31.5	34.5	37.4	40.3	43.0	45.8	48.5	51.1	55.0	61.5	1
26	Multiple				21.8	25.3	28.7	31.8	34.9	38.0	41.0	43.9	46.8	49.7	52.6	56.9	63.9	9
	Single				25.0	29.0	32.7	36.2	39.5	42.8	46.0	49.1	52.2	55.3	58.4	62.9	70.3	2
28	Multiple				25.2	29.0	32.7	36.3	39.8	43.2	46.6	49.9	53.3	56.6	59.9	64.8	72.9	4
	Single				28.8	33.1	37.1	41.0	44.7	48.4	52.0	55.6	59.1	62.6	66.0	71.2	79.8	4
30	Multiple				28.6	32.8	36.9	40.9	44.8	48.7	52.5	56.3	60.1	63.9	67.6	73.2	82.5	4
	Single				32.6	37.2	41.7	45.9	50.1	54.2	58.3	62.3	66.3	70.3	74.2	80.1	89.8	1
32	Multiple				32.1	36.8	41.3	45.8	50.1	54.5	58.8	63.1	67.3	71.6	75.8	82.2	92.7	3
	Single				36.5	41.5	46.4	51.1	55.8	60.4	64.9	69.4	73.9	78.4	82.8	89.5	100.5	0
35	Multiple				37.6	43.0	48.3	53.5	58.6	63.8	68.9	73.9	79.0	84.0	89.1	96.6	109.1	7
	Single				42.4	48.2	53.8	59.3	64.7	70.1	75.5	80.8	86.1	91.4	96.7	104.6	117.7	0
40	Multiple				47.4	54.2	60.9	67.6	74.2	80.8	87.4	94.0	100.6	107.1	113.6	123.4	139.7	0
	Single				52.9	60.1	67.2	74.2	81.2	88.1	95.0	101.8	108.7	115.5	122.4	132.6	149.6	0
Number of trees		34	51	97	93	78	74	57	20	19	11	2	4	1	3	0	1	545

Multiple-stem:

$$\text{Volume} = \begin{cases} -0.129 + 2.0255 \cdot X + 0.1011 \cdot X^2 & \text{for } X \leq 6 \\ 10\,786 + 2\,0255 \cdot X - 43.663/X & \text{for } X > 6 \end{cases}$$

where:

X = EDRC•EDRC•Height/1,000

Single-stem:

$$\text{Volume} = \begin{cases} -0.032 + 2.1076 \cdot X + 0.1454 \cdot X^2 & \text{for } X \leq 6 \\ 15.675 + 2.1076 \cdot X - 62.827/X & \text{for } X > 6 \end{cases}$$

where:

X = DRC•DRC•Height/1,000

Note: EDRC, DRC in inches and Height in feet.

Table 4—Mesquite outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet) 6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	Number of trees
Inches		*Cubic feet*																
4	Multiple	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8								12
	Single	.2	.3	.4	.4	.5	.6	.7	.8	.9								62
6	Multiple	.5	.6	.8	.9	1.1	1.3	1.5	1.7	1.9	2.1							49
	Single	.5	.7	.9	1.1	1.3	1.6	1.8	2.1	2.3	2.6							29
8	Multiple	.8	1.1	1.5	1.8	2.2	2.6	3.0	3.4	3.8	4.3	4.8						54
	Single	1.0	1.4	1.8	2.2	2.7	3.2	3.7	4.3	4.8	5.4	6.1						19
10	Multiple	1.4	1.9	2.5	3.1	3.8	4.5	5.3	6.1	6.9	7.6	8.3	8.9	9.5				34
	Single	1.6	2.3	3.1	3.9	4.8	5.8	6.8	7.8	8.9	9.8	10.7	11.5	12.3				11
12	Multiple	2.1	3.0	3.9	5.0	6.2	7.3	8.3	9.2	10.0	10.8	11.6	12.3	13.0	13.7	14.7	16.3	20
	Single	2.6	3.7	5.0	6.4	7.9	9.4	10.7	11.9	12.9	14.0	14.9	15.8	16.7	17.6	18.8	20.8	4
14	Multiple	3.0	4.4	5.9	7.5	8.8	9.9	11.0	12.0	13.0	13.9	14.8	15.7	16.5	17.4	18.6	20.6	11
	Single	3.8	5.6	7.6	9.6	11.3	12.8	14.2	15.5	16.7	17.9	19.0	20.1	21.1	22.2	23.8	26.3	3
16	Multiple	4.3	6.3	8.2	9.8	11.2	12.4	13.7	14.8	16.0	17.1	18.2	19.2	20.3	21.3	22.9	25.5	7
	Single	5.4	8.1	10.6	12.6	14.4	16.0	17.6	19.0	20.5	21.9	23.2	24.6	25.9	27.2	29.1	32.3	0
18	Multiple	5.9	8.3	10.2	11.9	13.5	15.0	16.4	17.8	19.2	20.5	21.8	23.1	24.4	25.7	27.6	30.8	2
	Single	7.5	10.7	13.2	15.4	17.4	19.2	21.0	22.8	24.4	26.1	27.8	29.4	31.0	32.6	35.0	38.9	3
20	Multiple				14.1	15.9	17.6	19.3	21.0	22.6	24.2	25.8	27.4	28.9	30.5	32.8	36.7	0
	Single				18.1	20.4	22.5	24.6	26.7	28.7	30.7	32.7	34.6	36.6	38.5	41.4	46.2	0
22	Multiple						20.4	22.4	24.3	26.3	28.2	30.1	32.0	33.8	35.7	38.5	43.2	0
	Single						26.0	28.5	30.9	33.3	35.6	38.0	40.3	42.6	45.0	48.4	54.2	0
24	Multiple						23.4	25.7	28.0	30.2	32.5	34.7	37.0	39.2	41.4	44.7	50.2	0
	Single						29.7	32.6	35.4	38.2	41.0	43.7	46.5	49.2	52.0	56.1	62.9	0
26	Multiple								31.9	34.5	37.1	39.7	42.4	44.9	47.5	51.4	57.9	0
	Single								40.2	43.5	46.7	49.9	53.2	56.4	59.6	64.4	72.3	0
28	Multiple								36.1	39.1	42.1	45.1	48.2	51.2	54.2	58.7	66.1	0
	Single								45.4	49.2	52.9	56.6	60.3	64.0	67.7	73.3	82.5	0
30	Multiple								40.6	44.0	47.5	50.9	54.4	57.8	61.2	66.4	75.0	1
	Single								51.0	55.2	59.5	63.7	68.0	72.2	76.5	82.8	93.4	0
32	Multiple								45.3	49.3	53.2	57.1	61.0	64.9	68.8	74.7	84.4	0
	Single								56.8	61.7	66.5	71.3	76.2	81.0	85.8	93.0	105.0	0
Number of trees		36	46	77	63	45	24	16	2	8	1	0	1	1	0	1	0	321

Multiple-stem:

$$\text{Volume} = \begin{cases} 0.020 + 1.8972 \cdot X + 0.5756 \cdot X^2 & \text{for } X \le 2 \\ 6.927 + 1.8972 \cdot X - 9.210/X & \text{for } X > 2 \end{cases}$$

where:

X = EDRC•EDRC•Height/1,000

Single-stem:

$$\text{Volume} = \begin{cases} -0.043 + 2.3378 \cdot X + 0.8024 \cdot X^2 & \text{for } X \le 2 \\ 9.586 + 2.3378 \cdot X - 12.839/X & \text{for } X > 2 \end{cases}$$

where:

X = DRC•DRC•Height/1,000

Note: EDRC, DRC in inches and Height in feet.

Table 5—Oak outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet)																Number of trees
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	
Inches		*Cubic feet*																
4	Multiple	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7							7
	Single	.2	.2	.3	.4	.5	.6	.6	.7	.8	.9							48
6	Multiple	.4	.5	.7	.8	1.0	1.1	1.3	1.5	1.6	1.8							22
	Single	.5	.6	.8	1.0	1.2	1.4	1.5	1.7	1.9	2.1							47
8	Multiple	.7	1.0	1.3	1.6	1.8	2.1	2.4	2.7	3.0	3.3	3.6						27
	Single	.9	1.2	1.5	1.9	2.2	2.5	2.9	3.2	3.6	4.0	4.3						39
10	Multiple	1.2	1.6	2.1	2.5	3.0	3.5	3.9	4.4	4.9	5.5	6.0	6.5	7.1				20
	Single	1.4	1.9	2.5	3.0	3.6	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.4				32
12	Multiple	1.8	2.4	3.1	3.8	4.5	5.2	6.0	6.8	7.6	8.4	9.3	10.1	11.0	11.8	13.0	14.8	30
	Single	2.1	2.9	3.7	4.5	5.3	6.2	7.1	8.0	8.9	9.9	10.9	11.9	12.9	13.8	15.2	17.3	17
14	Multiple		3.4	4.3	5.3	6.4	7.5	8.6	9.8	11.0	12.1	13.1	14.2	15.1	16.1	17.5	19.7	21
	Single		4.0	5.2	6.4	7.6	8.8	10.1	11.5	12.8	14.1	15.4	16.5	17.7	18.8	20.5	23.2	11
16	Multiple		4.6	5.9	7.3	8.8	10.3	11.8	13.2	14.5	15.8	17.0	18.2	19.4	20.5	22.2	25.0	3
	Single		5.4	7.0	8.6	10.3	12.1	13.8	15.4	17.0	18.5	19.9	21.3	22.7	24.1	26.1	29.5	6
18	Multiple			7.8	9.7	11.6	13.4	15.0	16.6	18.1	19.6	21.0	22.4	23.8	25.2	27.3	30.6	3
	Single			9.2	11.4	13.6	15.6	17.6	19.4	21.2	23.0	24.7	26.4	28.1	29.8	32.3	36.4	4
20	Multiple			10.0	12.3	14.4	16.4	18.3	20.1	21.9	23.6	25.3	27.0	28.7	30.3	32.8	36.8	5
	Single			11.8	14.4	16.9	19.2	21.4	23.6	25.7	27.8	29.9	31.9	34.0	36.0	39.0	43.9	3
22	Multiple			12.4	15.0	17.3	19.5	21.7	23.8	25.8	27.9	29.9	31.9	33.8	35.8	38.7	43.6	1
	Single			14.6	17.5	20.3	22.9	25.5	28.0	30.5	33.0	35.4	37.9	40.3	42.7	46.3	52.2	2
24	Multiple						22.8	25.2	27.7	30.0	32.4	34.8	37.1	39.4	41.7	45.2	50.9	0
	Single						26.8	29.8	32.7	35.6	38.5	41.4	44.3	47.1	49.9	54.2	61.2	0
26	Multiple						26.2	29.0	31.8	34.6	37.3	40.0	42.7	45.4	48.1	52.2	58.9	0
	Single						30.9	34.4	37.8	41.1	44.5	47.8	51.2	54.5	57.8	62.7	70.9	2
28	Multiple						29.8	33.0	36.2	39.4	42.5	45.7	48.8	51.9	55.0	59.7	67.4	0
	Single						35.3	39.3	43.1	47.0	50.9	54.7	58.6	62.4	66.2	71.9	81.4	0
Number of trees		25	42	61	70	53	38	26	13	3	8	1	4	2	0	3	1	350

Multiple-stem:

$$\text{Volume} = \begin{cases} -0.028 + 1.9545 \cdot X + 0.1400 \cdot X^2 & \text{for } X \le 4 \\ 6.691 + 1.9545 \cdot X - 17.918/X & \text{for } X > 4 \end{cases}$$

where:

X = EDRC•EDRC•Height/1,000

Single-stem:

$$\text{Volume} = \begin{cases} -0.068 + 2.4048 \cdot X + 0.1383 \cdot X^2 & \text{for } X \le 4 \\ 6.571 + 2.4048 \cdot X - 17.704/X & \text{for } X > 4 \end{cases}$$

where:

X = DRC•DRC•Height/1,000

Note: EDRC, DRC in inches and Height in feet.

Table 6—Pinyon outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet)																Number of trees
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	
Inches		*Cubic feet*																
4	Single/ Multiple	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1					84
6	Single/ Multiple	.5	.7	.9	1.1	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8				43
8	Single/ Multiple	.9	1.3	1.6	2.0	2.3	2.7	3.0	3.4	3.8	4.1	4.5	4.9	5.3	5.7			36
10	Single/ Multiple		2.0	2.6	3.2	3.7	4.3	4.9	5.6	6.2	6.8	7.5	8.1	8.8	9.5	10.4		29
12	Single/ Multiple			3.9	4.7	5.6	6.5	7.4	8.4	9.4	10.3	11.2	12.1	12.9	13.8	15.0	17.0	18
14	Single/ Multiple			5.4	6.7	7.9	9.3	10.5	11.7	12.9	14.0	15.2	16.3	17.3	18.4	20.0	22.6	10
16	Single/ Multiple				9.0	10.7	12.3	13.8	15.2	16.7	18.1	19.4	20.8	22.2	23.5	25.5	28.9	2
18	Single/ Multiple				11.6	13.6	15.4	17.2	19.0	20.7	22.4	24.1	25.8	27.5	29.2	31.7	35.9	1
20	Single/ Multiple				14.3	16.6	18.7	20.9	23.0	25.1	27.2	29.3	31.3	33.4	35.5	38.5	43.6	1
22	Single/ Multiple							24.9	27.4	29.9	32.4	34.9	37.4	39.9	42.3	46.0	52.2	0
24	Single/ Multiple							29.2	32.2	35.1	38.1	41.0	44.0	46.9	49.8	54.2	61.5	1
26	Single/ Multiple							33.8	37.3	40.8	44.2	47.6	51.1	54.5	57.9	63.0	71.6	1
28	Single/ Multiple							38.8	42.8	46.8	50.8	54.8	58.7	62.7	66.7	72.6	82.5	0
Number of trees		10	30	45	35	25	17	22	12	10	10	2	3	1	1	3	0	226

$$\text{Volume} = \begin{cases} -0.060 + 2.5139 \cdot X + 0.1466 \cdot X^2 & \text{for } X \leq 3 \\ 3.898 + 2.5139 \cdot X - 7.917/X & \text{for } X > 3 \end{cases}$$

where:

$$X = \begin{cases} \text{DRC} \cdot \text{DRC} \cdot \text{Height}/1{,}000 & \text{for single-stem trees} \\ \text{EDRC} \cdot \text{EDRC} \cdot \text{Height}/1{,}000 & \text{for multiple-stem trees.} \end{cases}$$

Note: EDRC, DRC in inches and Height in feet.

Chojnacky, David C. 1988. Juniper, pinyon, oak, and mesquite volume equations for Arizona. Res. Pap. INT-391. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Volume prediction equations have been developed for Arizona's juniper, pinyon, oak, and mesquite woodland tree species. The equations require measurements of total tree height and tree diameter near the root collar. Results are presented in equation and tabular formats. Volume equation construction, volume equation reliability, and comparison of the results with other studies are discussed.

KEYWORDS: *Juniperus, Pinus edulis, Prosopis, Acacia, Olneya, Quercus,* volume table, Cook's-D, weighted regression

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

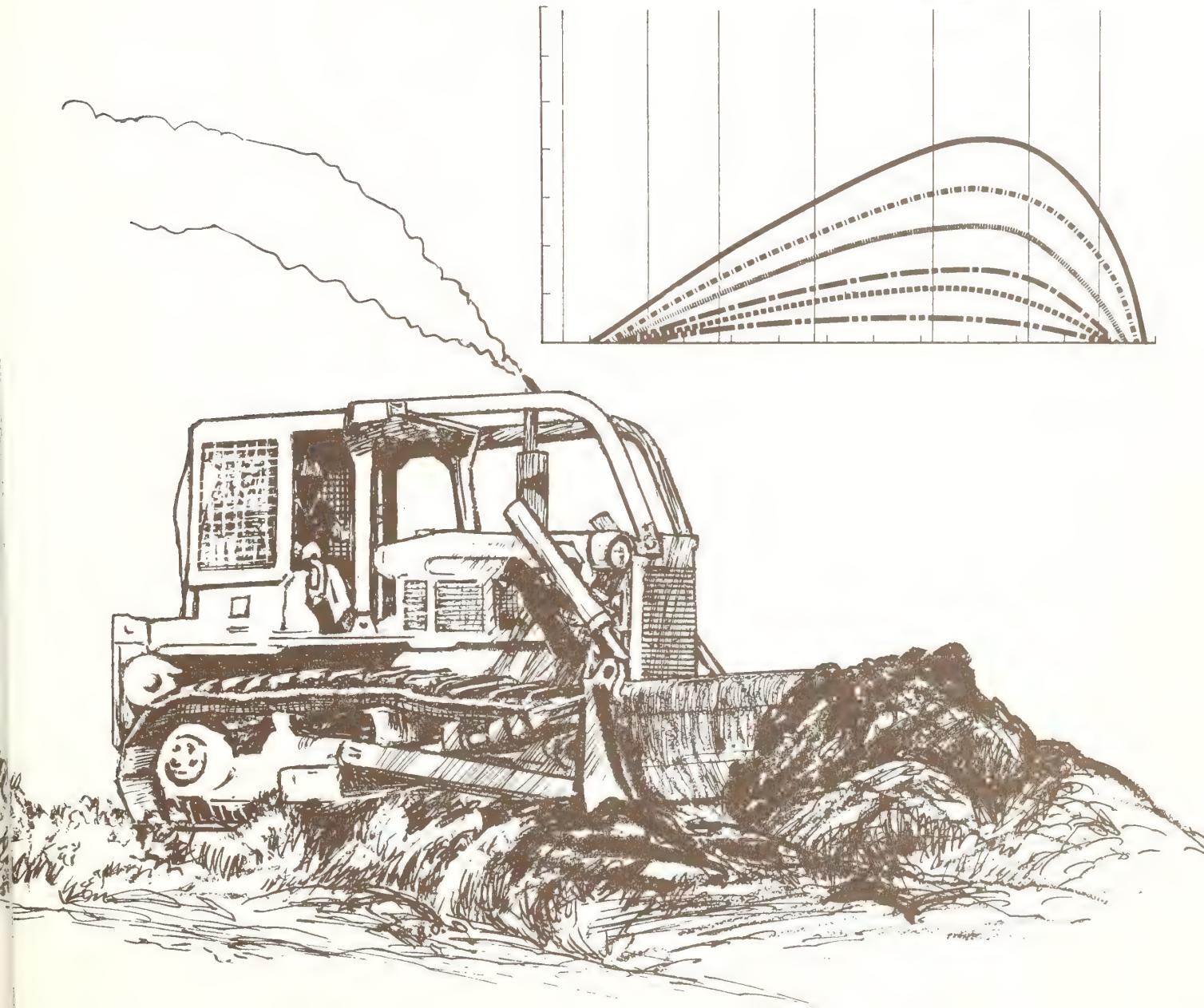
Research Paper
INT-392

June 1988

Bulldozer Fireline Production Rates—1988 Update

**Clinton B. Phillips
Charles W. George
David K. Nelson**

CLEMSON UNIVERSITY
AUG 17 1988
PUBLIC DOCUMENTS



THE AUTHORS

CLINTON B. PHILLIPS received a B.S. degree in forestry from the University of California, Berkeley, in 1947, at which time he was employed by the California Department of Forestry. During his 35 years with that department, he was a ranger unit manager, was assigned for 2 years to the Pacific Southwest Forest and Range Experiment Station in Berkeley to manage several fire research studies, was the department's fire research coordinator for 12 years, and was Assistant Chief of Fire Protection for the department for the last 10 years of his career. He is currently a consultant in rural and wildland fire protection and fire management planning.

CHARLES W. GEORGE received his B.S. degree in forest engineering in 1964 and M.S. degree in forestry in 1969. He joined Intermountain Station's staff in 1965 where he has conducted studies related to prescribed fire, pyrolysis and combustion, fire retardants, and aerial delivery systems. Presently Mr. George is Project Leader of the Fire Suppression Research Work Unit at the Intermountain Fire Sciences Laboratory, Missoula, MT. The current mission of the work unit is to develop the knowledge and systems that will improve fire control capabilities and facilitate fire management planning, with emphasis on improving chemical fire suppression technology.

DAVID K. NELSON received a B.S. degree in forestry from Iowa State University in 1959. Since then he has worked for the USDA Forest Service in the Pacific Southwest Region as a smokejumper, a District Timber Management Officer on the Shasta-Trinity National Forest, the Smokejumper Unit Supervisor at the Northern California Service Center, District Ranger on the San Bernardino National Forest, and is currently the Forest Fire Management Officer on the Tahoe National Forest. During this period he was a member of a Regional Fire/Incident Management Team for 12 years, of which 9 were as a Fire Boss/Incident Commander. In addition he has had special assignments such as the Regional Fire Equipment Committee, the National Wildlife Coordinating Group Incident Command System Working Team, and the 1970 National Fire Planning Development Team.

RESEARCH SUMMARY

Bulldozers are an effective but expensive machine for building fireline; therefore, it is important for fire managers to have some means of estimating the rate at which various sizes of bulldozers can build fireline in different fire behavior fuel models and slope classes. Handbooks and reports currently available show bulldozer production rates that are revisions of studies made in the late 1950's and late 1960's. Not only are the production rates in those handbooks and reports outdated, they also present illogical combinations of fire behavior fuel models, and they do not differentiate major differences in production rates for upslope and downslope operation.

The goal of this study was to develop production rates for bulldozers manufactured since 1965, and especially for those manufactured since 1975. Tentative rates that were derived mathematically were published in 1984. Verification of those rates was tested in the field, measuring the production rates for bulldozers as they constructed firelines around prescribed fires. This report presents a revised table of production rates based on the results of the field tests. The table gives a range of production rates for three size-classes of bulldozers, a more logical set of combinations of the 13 fire behavior fuel models and four slope classes (both upslope and downslope), and specifies rules for selecting proper rates from the tables for different sets of field conditions.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Bulldozer Fireline Production Rates—1988 Update

Clinton B. Phillips
Charles W. George
David K. Nelson

INTRODUCTION

In recent years, the use of bulldozers to construct firelines around wildland fires or prescribed fires has been curtailed in some fragile ecosystems. The heavy machines are still valuable in many situations, however, especially for moving large volumes of vegetation in a comparatively short time while constructing a fireline to mineral soil (fig. 1). For planning purposes wildland fire managers need to know the rates at which bulldozers can be expected to construct firelines in different combinations of vegetation, slope, and soil. Unfortunately, recent fireline handbooks and other publications (British Columbia Forest Service 1976; National Wildfire Coordinating Group 1980; Schmidt and Rinehart 1982; USDA Forest Service 1980) have presented production rates based upon studies made some 20 to 40 years ago (California Division of Forestry 1967; USDA Forest Service 1948). The rates in those publications do not apply to more modern bulldozers, are presented in a form that ignores important differences in rates of constructing firelines upslope and downslope, and in some cases are confusing in their relation to various fuel models.

In 1982-83 an effort was made to update older rates of fireline construction for bulldozers. Tentatively updated rates were published in the report by Phillips and Barney (1984). Those rates, shown in tables 1 and 2, were derived mathematically in the following manner:

1. Rates obtained in earlier field studies were selected as "base rates" (California Division of Forestry 1967; Steele 1961).
2. The base rates were adjusted to fit newer models of bulldozers by using production indexes established by the manufacturers of bulldozers for earth-moving applications.
3. The adjusted rates were related to four variables:
   a. Each of the 13 fire behavior fuel models (Anderson 1982).
   b. Both upslope and downslope construction of firelines.
   c. The first three slope classes of the National Fire-Danger Rating System (Deeming and others 1977).
   d. Three size classes of bulldozers arbitrarily established by using the following criteria:

Figure 1—Bulldozer constructing fireline through light fuel around an area scheduled for prescribed burning.

Criteria	Size class		
	Small	Medium	Large
Weight (tons)	5-10	11-20	21-40
Net horsepower	55-95	100-195	200-350
Blade width (ft)	8-9	10-12	13-16
Track gauge (ft)	5+	6+	7+
Track area on ground (in^2)	1,500-2,900	3,000-4,200	4,300-6,300
NIIMS type	3	2	1

Many other conditions were held constant and were consistent with the studies of Steele and the Studies of the California Division of Forestry: single-pass fireline, indirect line location, only the best qualified operators, equipment in good operating condition, no lost time, average fire behavior, dry soil with reasonably good traction and no rock obstacles, air temperature ranging from 85 to 105 °F (29 to 41 °C), and line construction during daylight hours only. The rates were published in two tables (republished as tables 1 and 2 in this report). It was noted that if actual conditions varied from the assumed conditions, then the production rates would have to be adjusted accordingly. The magnitude of adjustment was not indicated. Field verification of the tentative rates started in the summer of 1983 and continued through 1986. This report reflects the results of those field studies and presents revisions to the tables published in 1984.

PLANNING AND CONDUCTING THE VERIFICATION STUDY

As part of the initial study, a procedure was developed for testing bulldozer fireline production rates (Phillips 1983). Based upon techniques used in the earlier studies of bulldozers (California Division of Forestry 1967; Steele 1961), the procedure would require a minimum of 3 days of field tests, at least three bulldozers (one each small, medium, and large size), 18 people, a considerable array of supporting equipment, fuel and servicing for bulldozers and other vehicles, and expenses for travel, housing, meals, and general logistical support. Also the tests would require an extensive area of land, including several fuel models, which would be disturbed considerably by the bulldozers building fireline to mineral soil. For comparison, during 5 weeks in the summer of 1967, the California Department of Forestry tested four small and three medium bulldozers which involved 45 people in an area of several hundred acres. The decision was made in 1983 that such a field study was desirable but beyond the fiscal ability of the USDA Forest Service to perform at that time.

Another alternative was selected. The field verification of bulldozer fireline production rates would be made by following bulldozers as they constructed lines around

Table 1—Bulldozer fireline production rates (single pass) for bulldozers manufactured since 1975

Fire behavior fuel model	Slope class 1 (0-25%)		Slope class 2 (26-40%)		Slope class 3 (41-55%)	
	Up	Down	Up	Down	Up	Down
	Chains per hour					
Small bulldozers						
1, 2, 3	63	88	36	88	14	61
4	22	29	12	30	3	22
5	63	88	36	88	14	61
6	39	59	22	62	8	42
7	39	52	22	56	8	35
8	63	88	36	88	14	61
9,11,12	22	30	12	30	3	11
Medium bulldozers						
1, 2, 3	88	118	58	112	35	73
4	32	47	18	53	5	31
5	88	118	58	112	35	73
6	51	75	26	78	9	48
7	51	75	27	78	9	48
8	88	118	58	112	35	73
9, 11, 12	32	47	18	53	5	31
10,13	17	23	10	25	3	11
Large bulldozers						
1, 2, 3	91	124	62	118	35	83
4	43	60	27	62	12	40
5	91	124	62	118	35	83
6, 7	63	91	41	90	22	57
8	91	124	62	118	35	83
9, 11,12	43	60	27	62	12	40
10, 13	27	38	15	34	4	16

Table 2—Bulldozer fireline production rates (single pass) for bulldozers manufactured since 1965-75

Fire behavior fuel model	Slope class 1 (0-25%)		Slope class 2 (26-40%)		Slope class 3 (41-55%)	
	Up	Down	Up	Down	Up	Down
	Chains per hour					
Small bulldozers						
1, 2, 3	63	88	36	88	14	61
4	22	29	12	30	3	22
5	63	88	36	88	14	61
6	41	57	22	58	8	37
7	41	57	22	58	8	37
8	63	88	36	88	14	61
9, 11, 12	22	30	12	29	3	13
Medium bulldozers						
1, 2, 3	85	112	57	107	34	71
4	30	44	16	50	4	30
5	85	112	57	107	34	70
6	49	72	26	75	7	47
7	49	72	26	75	7	47
8	85	112	57	107	34	71
9, 11, 12	30	44	16	50	4	30
10, 13	17	25	11	24	3	9
Large bulldozers						
1, 2, 3	82	111	55	105	32	74
4	38	54	24	55	11	36
5	82	111	55	105	32	74
6, 7	57	82	37	80	20	51
8	82	111	55	105	32	74
9, 11, 12	38	54	24	55	11	36
10,13	24	34	13	30	4	14

planned prescribed fires and going wildfires. This alternative, while within the study's fiscal constraints, had some serious shortcomings as it turned out.

Early in the verification study it became evident that following bulldozers around going wildfires was not too practical. First, during the years of the study, few wildfires occurred that were reachable by the study's observer before the fires were contained. On two fires that the observer was able to reach quickly, bulldozers were used only to place protective lines around residences. Several times the observer was traveling and was not available when potential situations for study arose; that was the case especially in the summer of 1985 when so many large wildland fires occurred in California. For those and other reasons, the verification study was confined to recording bulldozer production rates during the construction of firelines around planned prescribed fires in northern California.

The study's observer established a network of people who were involved in fuel management programs throughout northern California. Regular contacts were made with 15 Ranger Districts in seven National Forests of the Forest Service and nine Ranger Units in three Regions of the California Department of Forestry. Each spring, telephone calls were made to learn which administrative units would probably use bulldozers to construct lines around planned prescribed fires. Followup calls were then made throughout the spring, summer, and fall months, as needed, to determine exact days, times, and locations of work to be done.

From these contacts one fact soon became clear: both the Forest Service and the California Department of Forestry no longer use bulldozers to construct firelines around prescribed fires to the extent that they did just a few years ago. Two primary reasons emerged: (1) at a time of reduced budgets bulldozers are increasingly expensive to operate, and (2) bulldozers often disturb the soil to an unacceptable degree. Because bulldozers are an expensive tool, the Forest Service has reduced in recent years the number of machines it owns and depends more on contractual equipment. In the case of the California Department of Forestry, that agency allows private landowners to use their own bulldozers to construct lines around prescribed fires as the landowner's major contribution to the overall cost of a cooperative fuel management project. As the study soon revealed, private bulldozers are sometimes old, poorly maintained, and operated with a relatively low level of skill. Production rates obtained from most of them are therefore not too comparable to the rates in the published tables.

As another means of reducing use of their own bulldozers, both the Forest Service and the California Department of Forestry rely more on established roads or natural breaks in laying out the perimeters of prescribed fires. That technique may produce a prescribed fire that is larger or a different shape than originally planned, but it meets the agencies' objectives of reducing the costs of prescribed fires and of reducing soil disturbance. The result, in terms of the verification study, was fewer opportunities to study bulldozer production rates than might have been expected in the recent past.

Another objective of the verification study was to make at least some tests at night. Such tests were attempted on two occasions, but it was found that required observations simply could not be made well at night. The primary problem was the refraction of the bulldozer's lights and the observer's flashlight through the thick cloud of dust. It was difficult or impossible to see well enough to anticipate when the slope was changing 5 percent or more, to identify landmarks for measuring points of slope changes and distances, and to read the Abney level. Consequently, only one set of data and some general observations were obtained for night operations.

The study's observer sought and managed to find a range of operating conditions. Bulldozers varied widely in terms of manufacturer, age, and operating condition. There was a wide range in the experience and skill of the operators, perhaps the single most important factor influencing bulldozer production rates. Soil conditions were also very important in influencing production rates. At two locations, granite boulders were so large and numerous that constructing any sort of a control line was an accomplishment; production rates were, not unexpectedly, exceedingly slow. At the other extreme, certain firelines were constructed with ease. During the spring of 1986, at a site where the soil was still damp from an abnormally wet winter, bulldozers obtained excellent traction and had little difficulty in uprooting heavy chaparral from the moist soil. Observed production rates were much greater than those found in tables 1 and 2. Air temperature throughout the verification tests was never a limiting factor in the operation of the bulldozers, generally ranging between 80 to 96 °F. Air temperature above 100 °F causes some bulldozers to overheat and produce slower rates of line construction.

Table 3 shows the form designed for recording and calculating data, along with typical data and remarks.

Information about the bulldozer was desirable to establish the machine's age, operating characteristics, and which curve of production rates (Phillips and Barney 1984) should be used. Although it was impossible to measure each machine's mechanical condition, it was assumed that both the USDA Forest Service and the California Department of Forestry provided a high level of maintenance. Conversations with both agencies' employees and inspection of maintenance books for a few machines generally confirmed that fact. Perhaps the best subjective measure of operator skill was years of experience, as observed during the four summers of the study.

A "line" was arbitrarily defined as a major segment of a prescribed fire's perimeter, generally from one road or anchor point to another. A "run" within a line was defined as being wholly (or nearly so) within one fuel model and within a 5 percent slope. Whenever either of those two criteria changed, a new run was recorded (table 3). Most often the study's observer did all the measuring and recording while following a bulldozer. Agency representatives occasionally assisted the observer, especially in measuring distances, as their time permitted.

Data for columns 1, 2, 3, 4, 6, and 9 of the tally sheet were recorded in the field. Numbers for columns 5, 7, 10, 11, 12, and 13 were calculated later. The fire behavior fuel model was selected in agreement with the agency's

Table 3—Tally sheet for recording bulldozer fireline production rates in verification study[1]

Bulldozer size (circle one): S M L

Line No. _____

Make, Model, Year _____

General location _____

Serial No. _____

Hour reading, start: _____

finish: _____

Date _____

Operator's name _____

Observers _____

Years of experience _____

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
				NFDRS	Time of run					Production rate (chains/hour)		
	Fire behavior			slope		Mins	Hour	Distance				
Run	fuel model	Slope		class	Min:Sec	(0.01)	(nearest 0.001)	Slope	Horizontal	Test	Table	±Δ%
		Percent	*Degree*					*Ft*	*Chains*			
1	3	–5	–3	–1	1:40	1.67	0.028	200	3.03	108	118	–8
2	4	–30	–17	–2	4:03	4.05	.068	197	2.85	42	53	–21
3	4	–15	–9	–1	3:30	3.50	.058	153	2.29	39	47	–17
4	4	–51	–27	–3	5:00	5.00	.083	305	4.12	50	31	+61
5	1	+22	+12	+1	3:44	3.73	.062	351	5.20	84	75	+12
6	1	–5	–3	–1	7:48	7.80	.130	1119	16.93	130	108	+20

Air temperature about 92 °F. Run No. 1 in annual oats about 3-4 feet high. Runs Nos. 2-4 in mature chaparral up to 30 ft high consisting of manzanita, ceanothus, live oak, coffeeberry, toyon, and poison oak. Runs Nos. 2 and 3 had a few outcrops of "tombstone shale" angled upward toward dozer's blade. Runs Nos. 5 and 6 in shorter grass in poor soil.

[1]Cols. 1, 2, 3, 4, 6, 9 = field observations;
Cols. 5, 7, 8, 10, 11, 12, 13 completed in office;
Col. 10: Horizontal dist. (chains) = slope dist. (ft) x cos slope (°) ÷ 66.

representative, using the publication by Anderson (1982). Slope was observed with an Abney level (usually aiming at an established point on the rear of the bulldozer) and recorded in both percentage (for use with the production curves and to establish the slope class of the National Fire-Danger Rating System) and degrees (for calculating the horizontal distance in column 10 of the tally sheet). Time was observed with a stop watch in minutes and seconds (column 6) and then converted to hours (column 8) for use in calculating the production rate (column 11). Slope distance was measured with a 100-foot tape on steep and rocky slopes, with frequently tested pacing on less demanding slopes. To obtain horizontal distance in chains, the slope distance in feet was multiplied by the cosine of the slope angle in degrees and divided by 66 (a handheld scientific calculator was helpful!). The production rates in column 11 were calculated by dividing the horizontal distance (column 10) by time (column 8). The calculated rates were then compared to the adjusted rates (column 12) taken from the appropriate curve (Phillips and Barney 1984).

The adjusted rates were taken from the curves in figures 12-17 of the 1984 publication and not from tables 4 and 5 of that publication. That procedure was used so that the rates would be more closely related to the actual slope recorded in column 3 of the tally sheet. The rates recorded in tables 1 and 2 were only for the midpoints of the broad slope classes and therefore would not be as accurate as rates taken from the appropriate points on the curves. The percentage difference between the adjusted rates (from the 1984 publication) and the observed rates (from the verification study) was recorded in column 13 of the tally sheet.

The limited opportunities to conduct verification studies in the field produced the number of tests shown in table 4. The runs and distances shown in table 4 were distributed by bulldozer size, fire behavior fuel model, and slope class as shown in table 5. As table 5 shows, few combinations of fuel models and slope classes were tested enough to permit a satisfactory verification of the adjusted rates in tables 1 and 2. Nevertheless, some broad interpretations of the data can be made.

Table 4—Tests made in 1983-86 to verify bulldozer fireline production rates

Year	Number locations	Number lines	Number runs	Horizontal distance
				Chains
1983	2	3	16	49.39
1984	3	5	38	223.40
1985	8	17	51	442.91
1986	3	16	91	736.39
Total	16	41	196	1,452.09

Table 5—The number of runs of three sizes of bulldozers observed during the verification study, distributed according to fire behavior fuel model and slope class

Fire behavior fuel model	Bulldozer size	Slope class 1 (0-25%)		Slope class 2 (26-40%)		Slope class 3 (41-55%)		Total runs	Total horizontal distance
		Up	Down	Up	Down	Up	Down		
									Chains
1	Medium	25	17	2	1			45	306.68
2	Small	3	2					5	19.20
	Medium	2	1					3	20.98
	Large	9	1					10	340.04
3	Medium	1	2		2	2	1	8	30.91
4	Small	4	3	13	16	3	3	42	206.44
	Medium	5	5	7	11	2	6	36	161.60
	Large		2		3			5	10.52
5	Medium	3	2		1			6	41.20
6	Medium	4	6		1			11	100.61
	Large	1						1	3.33
7	None								
8	None								
9	Medium	9	1					10	155.76
10	None								
11	Small		2		2			4	15.92
	Large	4	3	1	1			9	36.16
12	Large		1					1	2.74
13	None								
Total		70	48	23	38	7	10	196	1,452.09

RESULTS OF THE VERIFICATION STUDY

The primary objective of the verification study was to determine how well the observed bulldozer production rates calculated in column 11 of the tally sheet (table 3) compared with the adjusted rates in tables 1 and 2. This comparison is shown in table 6. In each cell of the table the average percentage difference of the observed rate is shown as being greater (+) or less (–) than the adjusted rate and is followed, in parentheses, by the number of runs from which the average percentage difference was derived. The average percentage difference was calculated from the percentage difference for each run, weighted by the length of the run in chains. Assuming that at least 10 runs were needed to provide a statistically valid average, then few cells in table 6 met that criterion. Even where the number of runs appeared adequate for statistical analysis, in many instances the data were conditional and needed careful interpretation for the various fire behavior fuel models (FBFM), as follows:

Fire Behavior Fuel Model 1—As table 6 shows, data for this fuel model were obtained only with medium bulldozers and almost entirely in slope class 1. Assuming the data in slope class 1 were accurate, however, the adjusted rates in tables 1 and 2 should be increased.

Fire Behavior Fuel Model 2—There were few data for this fuel model. Nevertheless, the direction of change seemed to be the same as for Fire Behavior Fuel Model (FBFM) 1. As observed in the field studies, there was little if any difference between FBFM's 1 and 2 in respect to their resistance to line construction by bulldozers.

Table 6—The average percent difference between bulldozer fireline production rates observed during the verification study and the adjusted rates from tables 1 and 2[1]

Fire behavior fuel model	Bulldozer size	Slope class 1 (0-25%)		Slope class 2 (26-40%)		Slope class 3 (41-55%)	
		Up	Down	Up	Down	Up	Down
1	Medium	+18%(25)	+3%(17)	+26%(2)	+30%(1)		
2	Small	+53%(3)	+24%(2)				
	Medium	+20%(2)	–41%(1)				
	Large	+154%(9)	+111%(1)				
3	Medium	–24%(1)	–15%(2)		–5%(2)	+10%(2)	–44%(1)
4[2]	Small	+97%(4)	+104%(3)	+113%(13)	+124%(16)	+251%(3)	+127%(3)
	Medium	+45%(5)	+63%(5)	+109%(7)	+52%(11)	+313%(2)	+102%(6)
	Large		–31%(2)		–66%(3)		
4[3]	Medium	+45%(5)	+62%(5)	+45%(4)	–5%(7)		+51%(2)
5	Medium	+20%(3)	–50%(2)		–30%(1)		
6[4]	Medium	–9%(4)	–9%(6)		–49%(1)		
	Large	+51%(1)					
6[5]	Medium	+36%(1)	+7%(3)		–49%(1)		
	Large	+51%(1)					
7	None						
8	None						
9	Medium	+107%(9)	+91%(1)				
10	None						
11	Small		–40%(2)		–24%(2)		
	Large	+3%(4)	–20%(3)	+23%(1)	–19%(1)		
12	Large		–31%(1)				
13	None						

[1]Percentages in the table are the percent differences in bulldozer fireline production rates followed, in parentheses, by the number of runs observed to obtain those differences.

[2]Includes observations made at a site where soil was moist, providing bulldozers with excellent traction and easing the uprooting and moving of heavy chaparral.

[3]Includes observations made only at sites where the soil was summer-dry.

[4]Includes observations made at two sites where there was a continuous expanse of large granitic boulders, atypical of most wildland fires in this fuel model.

[5]Includes observations made at sites where the soil contained amounts and sizes of rocks more typical of where wildland fires occur in California.

Therefore, the authors continued to combine those two fuel models for the purpose of publishing bulldozer fireline production rates.

Fire Behavior Fuel Model 3—Few data were obtained for this fuel model. The sparse number of observations indicated, however, that FBFM 3 should be separated from FBFM's 1 and 2 (they are together in tables 1 and 2) and given a slower production rate.

Fire Behavior Fuel Model 4—Unfortunately, most of the data obtained for this fuel model (shown in table 6 on the line for FBFM 4[2]) came from one site where the soil was still damp from the above-normal precipitation of the previous winter and spring. The moist soil provided excellent traction for the small and medium bulldozers that were observed and also allowed the machines to easily uproot or cut the stems of the tall (12 to 20 feet), mature chaparral. Because of the moist soil and the cool air temperature (80 °F), the observed production rates at that site were phenomenally good, even at slopes of 55 percent for the medium bulldozers. If nothing else, the observations at that site confirmed the much higher production rates to be expected from bulldozers when operating in moist soils with few inhibiting rocks. Although the authors preferred not to include those data in their consideration of changes to be made to the rates in tables 1 and 2, it was clear from observations at other sites (shown in table 6 on the line for FBFM 4[3]) that the rates for FBFM 4 needed to be increased.

Fire Behavior Fuel Model 5—A shortage of data for this fuel model did not provide a basis for changing the adjusted rates in tables 1 and 2. If any adjustments were to be made, the few data indicate that adjusted rates should be increased slightly for upslope production in slope class 1, and that downslope rates should be decreased for slope classes 1 and 2.

Fire Behavior Fuel Model 6—Large granite boulders presented formidable obstacles at two of the four sites where bulldozers were observed in this fuel model. The boulders caused production rates that were consistently 40 to 50 percent below the adjusted rates in tables 1 and 2. If nothing else, the observations at those two rocky sites gave good measures of the differences in production rates to be expected between very rocky terrain and the assumed condition of more favorable soil. Using only the few data obtained at the two sites where some rocks were present but not limiting, the observations indicated that the production rates for FBFM 6 should be increased for slope class 1 and possibly decreased for downslope operations in slope class 2. Those conclusions were not really valid, however, in light of the paucity of data.

Fire Behavior Fuel Model 7—This fuel model (southern rough) does not occur in California, and the normal tactical tool used to construct fireline is the tractor/plow. For the purpose of providing bulldozer production rates, however, the authors assume that the spacing of pine and other trees would not unduly restrict the passage of bulldozers. The resistance to fireline construction by bulldozers in this fuel model, therefore, would seem to be about the same as that in FBFM 6 (medium brush). With that reasoning, the authors combined FBFM's 6 and 7 in the display of fireline construction rates.

Fire Behavior Fuel Model 8—No data were gathered for this fuel model. Vegetational conditions for this model seem to offer only moderate resistance to bulldozer operation. As with FBFM 7, the authors assume that the spacing of trees in FBFM 8 would not unduly restrict the passage of bulldozers. The only obstacles would be occasional "jackpots" of accumulated dead fuel or small trees that might have to be pushed over. Based upon this assumption, bulldozer production rates in this fuel model could be combined with those in FBFM's 3 and 5.

Fire Behavior Fuel Model 9—The few data for this fuel model indicated that the adjusted rates in tables 1 and 2 were too low. At the three sites where observations were made in this fuel model, it was seen that medium-sized bulldozers, at least, could easily maneuver among the larger trees. Only occasionally was the construction of fireline slowed by the need to push over a sapling or two or to remove a fallen tree. For the most part, line construction was through the litter of leaves, needles, and fallen branches. Production rates, therefore, were consistently much faster than those shown in tables 1 and 2. Whether this increase in production rates would be true with large bulldozers is open to interpretation based upon spacing of large trees in this fuel model. If large bulldozers had been used at the same three sites as in this study, they should have been able to construct fireline at the same faster rates as observed for the medium bulldozers, in the observer's judgment.

Fire Behavior Fuel Model 10—No data were obtained for this fuel model. Therefore no changes should be made to the adjusted rates shown in tables 1 and 2.

Fire Behavior Fuel Model 11—Few data were obtained for this fuel model. The limited number of data indicated that large bulldozers might produce fireline at somewhat greater rates upslope for slope classes 1 and 2 than shown in tables 1 and 2, but at somewhat decreased rates downslope. The few data for small bulldozers also indicated slower production rates for downslope lines than those shown in tables 1 and 2.

Fire Behavior Fuel Model 12—The single observation made in a medium volume of slash did not permit any change to the production rates in tables 1 and 2 at this time.

Fire Behavior Fuel Model 13—No data were obtained for this heavy slash model. Therefore, no changes should be made at this time to the adjusted rates shown in tables 1 and 2.

One objective of the verification study was to confirm the absence of production rates for slope class 4 in tables 1 and 2. This slope class was omitted because the class' midpoint of 65.5 percent was at or above the maximum gradability for most bulldozers. The CDF's tests in 1967 showed that maximum gradability in light grass and favorable soil type averaged 75 percent for medium bulldozers with raised blades in forward gear; maximum gradability was about 65 percent in reverse gear. For small bulldozers the corresponding numbers averaged 67

percent in forward gear and 56 percent in reverse gear. Further, the 1967 study showed that line could be constructed up to a maximum gradability only if vegetation was light (low resistance to line construction) and soil conditions provided good traction. The 1967 study also showed that, while there was a gradual reduction in line production for steepening grades upslope, there was a gradual increase in line production for steepening grades downslope to the point where steepness caused bulldozer operators to have difficulty in backing up for the purpose of clearing their blades and taking another run at cleaning the line. Some bulldozer operators think that with angled blades they can work downslope without having to back up, thus they are not limited by maximum gradability in reverse gear. But if they hang up against a tree, stump, or rock, or suddenly lurch into a steep incline, or face a fire that has unexpectedly changed direction and is coming directly upslope toward them, they must be able to back up. Hence, maximum gradability in reverse gear is still an important limiting factor.

Maximum gradability was reviewed with equipment engineers and with instructors of bulldozer operation. They agreed unanimously that maximum gradability for newer machines has changed little since the CDF's tests in 1967. They found that operator's effectiveness and soil conditions were more important as limiting factors than recent improvements in bulldozer power, transmissions, tracks, and lubricating systems.

Nevertheless, there is room for effective line construction by bulldozers at least within the lower part of slope class 4. During the verification study one experienced operator was measured constructing line in FBFM 4 (tall, mature chaparral) at 55 percent grade, downslope, dry soil, at a rate of 44 chains per hour. That observation and several others around 50 percent slope, both upslope and downslope, confirmed that some production can be expected within slope class 4.

Given the few data from the verification study and the large number of important variables which affected those data, how could the fireline production rates for bulldozers be presented in a manner most useful to wildland fire managers, planners, and bulldozer operators? That question had to be answered before revising tables 1 and 2.

CRITERIA FOR DESIGNING TABLES OF BULLDOZER FIRELINE PRODUCTION RATES

Before designing a table of bulldozer fireline production rates the authors examined other published tables and also queried several wildland fire managers. From these examinations and discussions came the following criteria:

1. Differentiate the production rates by four variables:
   a. Three sizes of bulldozers.
   b. The 13 fire behavior fuel models.
   c. Slope classes of the National Fire-Danger Rating System.
   d. Direction of slope (upslope and downslope).
2. Keep the table simple, especially for fireline handbooks:
   a. Group the rates for as many fire behavior fuel models as practicable and reasonable.
   b. Round the rates off to the nearest 5 or 10 chains/hour.
   c. Have only one table of rates for all bulldozers of each size class; use a range of rates for each combination of the four variables listed above.

The authors found no difficulty in accepting the four variables to be used in the table. The three sizes of bulldozers, the 13 fire behavior fuel models, and the five slope classes of the National Fire-Danger Rating System are all well documented and accepted as standards by wildland fire managers.

But sometime in the past differentiation between upslope and downslope was dropped for bulldozer production rates. Why this happened has not been determined. As the rates in tables 1 and 2 show, there are substantial differences between upslope and downslope production within the same slope class. In slope class 1, production rates for downslope are as much as 50 percent greater than for upslope; in slope class 3, downslope rates are as much as 633 percent greater. Similar differences were shown in the Forest Service's Fireline Handbook (USDA Forest Service 1973) for Pacific Southwest Region as recently as June 1973. In at least three more recent publications, however, the upslope/downslope difference in production rates has been dropped and only a single rate given for each slope class (National Wildfire Coordinating Group 1980; Schmidt and Rinehart 1982; USDA Forest Service 1980). Because a single rate is not realistic, the authors have included both upslope and downslope rates in the final table in this report.

Side slopes may adversely affect line production by bulldozers, as reported by the CDF in 1967 (California Division of Forestry 1967). That agency's report said side slopes did not significantly affect upslope line production; downslope line production was reduced for side slopes of 30 percent or more, the amount of reduction depending on the balance of the individual bulldozer. During the verification study of 1983-86, no effort was made to measure the effect of side slope on production rates. In fact most line was constructed at right angles to the contours, and sideslope construction played a minor role.

Grouping bulldozer fireline production rates for two or more fire behavior fuel models seems feasible and, in fact, has been done in virtually every recently published table, including tables 1 and 2 of this report. After all, fire behavior fuel models were designed to reflect differences in expected fire behavior. They were not designed to give differences in the fuel models' resistance to line construction by bulldozers. For example, it is very evident that bulldozers should be expected to construct fireline at about the same rate in both fuel models 1 and 2, and the same thing should hold true for other combinations of fuel models. The tricky part comes in deciding what the combinations should be, especially in the absence of sufficient test data for production rates in some fuel models.

The recently published Federal tables (National Wildfire Coordinating Group 1980; Schmidt and Rinehart 1982; USDA Forest Service 1980) displayed some combinations of fuel models that are difficult to understand. Fuel model

2 (grass in open conifer), for example, was combined with fuel models 4 (mature chaparral), 9 (hardwood litter/conifers West), 11 (light slash), and 12 (medium slash). At a much lower rate of production (apparently judged to be more resistant to line construction by bulldozers) was fuel model 3 (tall grass) combined with, among others, fuel models 5 (low brush—why more difficult than fuel model 4, tall chaparral?), and 13 (heavy slash). The most difficult vegetative types for bulldozer line construction were judged to be fuel models 8 (timber litter in closed hardwoods) and 9 (hardwood litter); those two types had the lowest production rates for all three sizes of bulldozers.

Of the three recent Federal publications, only the NWCG Fireline Handbook (National Wildfire Coordinating Group 1980) provided a single production rate for each fire behavior fuel model (for each size of bulldozer and slope class). Apparently that single rate was an effort to fulfill the fire managers' plea for "simple tables" for field use. The other two publications (Schmidt and Rinehart 1982; USDA Forest Service 1980) recognized that each fire behavior fuel model was actually represented by a variety of vegetational types. Again, the vegetational varieties might be grouped from the standpoint of fire behavior but not necessarily according to their resistance to line construction by bulldozers. For example, it seems apparent that there may be significant differences in the rates for different vegetational types within fuel model 6 when you compare "southern hardwood shrub with pine slash residues" to "pinyon-juniper with sagebrush and grass intermixed." The former vegetational type presents a rather continuous fuel bed of resistive vegetation; in the latter vegetational type, a bulldozer can usually maneuver easily among scattered pinyon pine and juniper trees and construct fireline through the sparse sagebrush and grass at a comparatively fast rate of speed. And apparently there is a considerable difference to be expected in bulldozer production rates in fuel model 9 between hardwood litter in the Western States and in the Southern States; depending on bulldozer size and slope class, the Federal tables show rates are lower in the Southern States by 67 percent to 233 percent. The question is whether or not those differences are real.

So, if simplicity of tables of bulldozer production rates in fireline handbooks is to be achieved through combining fire behavior fuel models, great care must be given in how the task is accomplished.

Simplifying tables of production rates by rounding off rates to the nearest 5 or 10 chains/hour was easier to do. The suggestion came from fire managers who pointed out the large variance in bulldozer production rates. If a fire manager, using a table of bulldozer production rates, calculates that a particular fireline can be constructed in 4 hours, the actual time may turn out to be anywhere from 2 to 8 hours. The variation can occur because of operator skill, age and condition of the equipment, amount of rock outcrops encountered, condition and age of the vegetation, variations in vegetational type, number and density of large trees that have to be moved, air temperature, and so forth. Many of these variables can be evaluated, and appropriate adjustments can be made in the tabulated production rates and in the expected completion time. But then there are possibilities that do not enter into the equation, such as equipment breakdown or a rock outcrop that may stall a bulldozer's progress for hours. Basing their thinking on the many known variables, fire managers suggested that rates like "7" or "21" or "68" appeared to be precise, which they were not. Therefore, why not use "5," "20," and "70"? The latter set of numbers, they suggested, would be easier to use on actual fires. Perhaps they are right.

Finally, the fire managers suggested that there should be only a single table of production rates. They pointed out that the differences in rates shown in table 1 (for bulldozers manufactured since 1975) and table 2 (for bulldozers manufactured between 1965 and 1975) were not great. The differences in rates were certainly well within the variation caused by other factors such as operators' skills, vegetative types, soil types, etc. A single table, they suggested, could present a range of rates for each set of the four primary variables with rules about how to use the rates in relation to assumed and real conditions.

Considering the many variables affecting the effectiveness of bulldozers in the construction of firelines, it was somewhat difficult to provide what the fire managers sought: a simplified table of production rates.

REVISED TABLE OF BULLDOZER FIRELINE PRODUCTION RATES

Taking into account the observations made during the verification study, the characteristics of tables found in recent Federal publications, and comments by experienced fire managers, the authors recalculated bulldozer fireline production rates and prepared new curves (figs. 2-4). Table 7 was then constructed by reading from the curves the range of rates and the midpoint rate for each set of variables. The rates were rounded off to the nearest 5 chains/hour except for those rates below 10 chains/hour. At the bottom of the table are rules for using the range of rates. Those rules specify when to use higher rates within each range, when to use lower rates, and when to use the midpoints.

Table 7 shows the limitations of operating bulldozers in slope class 4. Fire managers wishing to plan for bulldozer operations in the lower range of slope class 4 may need to derive rates from the curves in figures 1-3. Generally, bulldozers will not be able to construct fireline at the upper range of slope class 4, either upslope or downslope, except under the most favorable conditions of soil (somewhat moist and no obstructing rocks) and air temperature (between 65 and 85 °F).

Table 7 does not differentiate among various vegetational types that may occur within a single fire behavior fuel model. That omission, done for the sake of simplicity in the table, can be a serious shortcoming. Users of the tables should use lower rates for the more resistive vegetative types within a fuel model and higher rates for less resistive types, as stated in the rules for using the table.

Admittedly, the curves and table are subjective compromises of all available data and information. Considering the many variables that affect the rates, however, they are reasonably accurate for use in fire management planning.

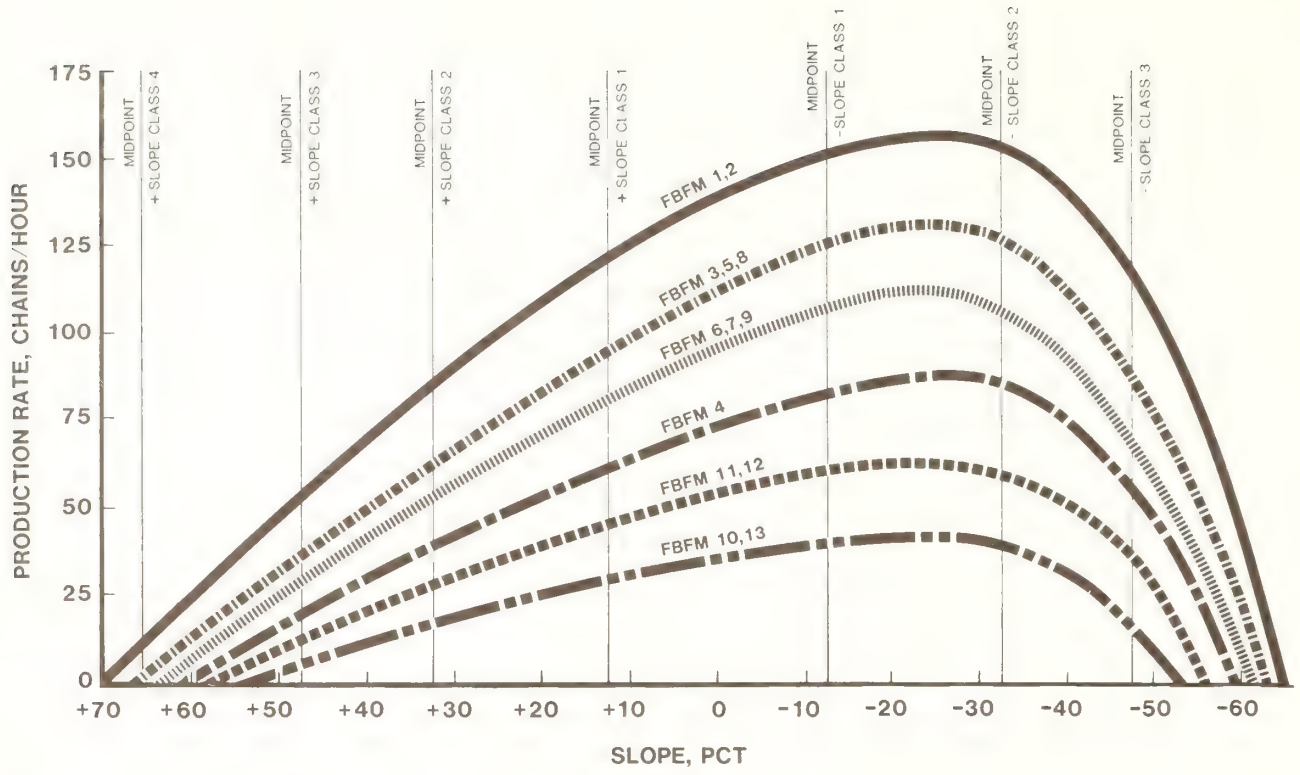


Figure 2—Production rates for large bulldozer, single pass.

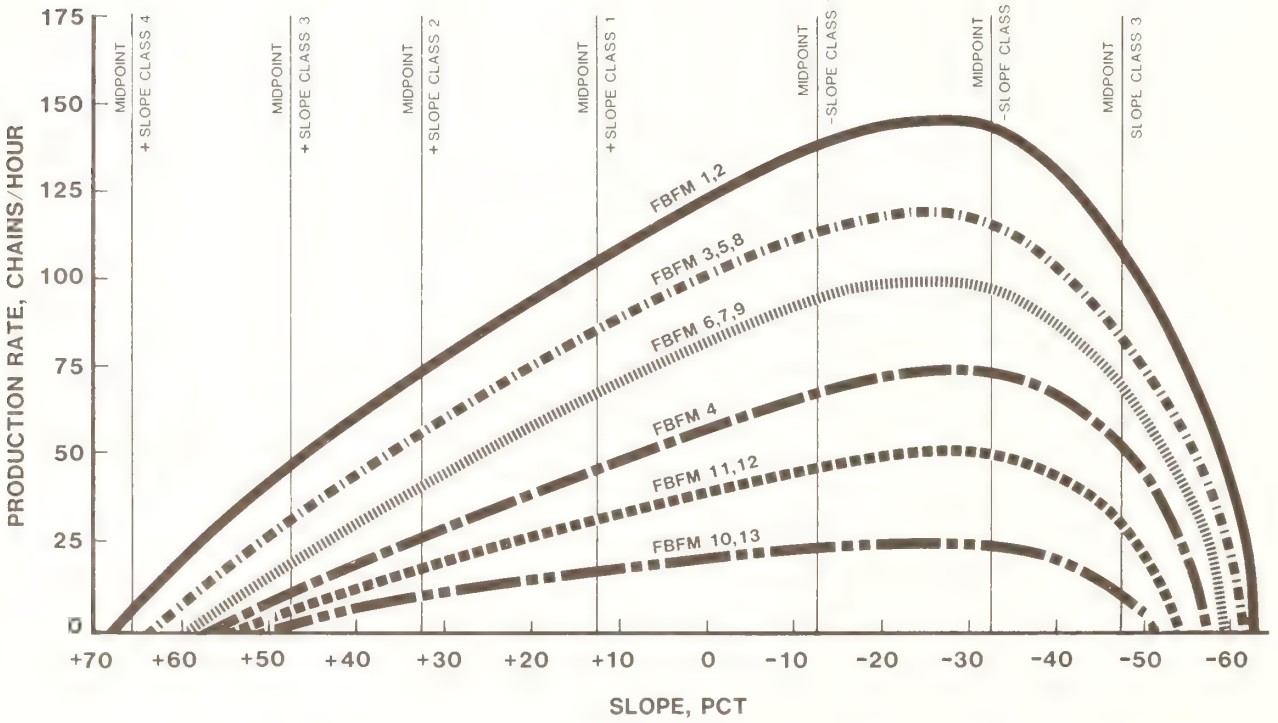


Figure 3—Production rates for medium bolldozer, single pass.

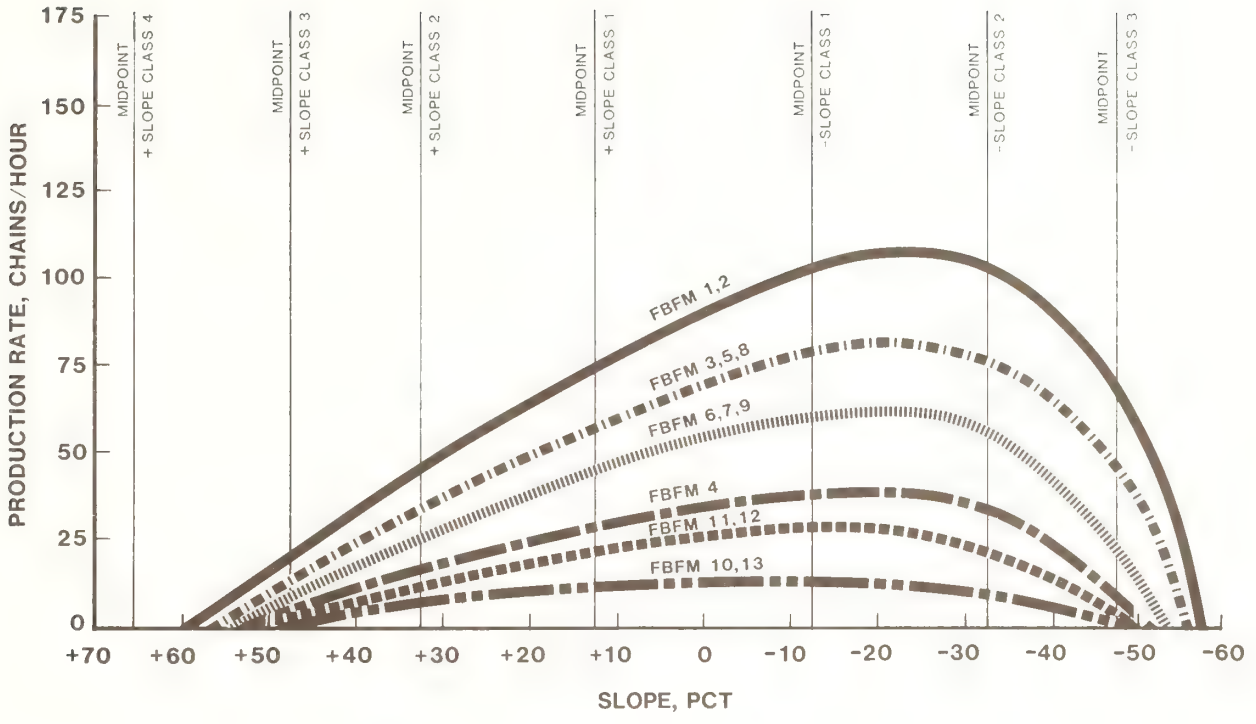


Figure 4—Production rates for small bulldozer, single pass.

Table 7—Bulldozer fireline production rates (single pass) in chains per hour; shown as a range of rates for each slope class, followed by the midpoint rate in parentheses

Fire behavior fuel model	Upslope or downslope	Slope class 1 (0-25%)	Slope class 2 (26-40%)	Slope class 3 (41-55%)	Slope class 4 (56-74%)
		Chains per hour			
Small bulldozers					
1, 2	Up	55-90(75)	30-55(45)	8-30(20)	0-8(0)
	Down	90-110(105)	90-110(105)	20-90(70)	0-20(0)
3, 5, 8	Up	45-70(60)	25-45(35)	2-25(10)	0-2(0)
	Down	70-80(80)	65-80(75)	0-65(45)	0
4	Up	20-35(30)	10-20(15)	0-10(4)	0
	Down	35-40(40)	25-40(35)	0-25(8)	0
6, 7, 9	Up	35-55(45)	15-35(25)	0-15(8)	0
	Down	55-60(60)	40-60(55)	0-40(20)	0
11, 12	Up	15-25(20)	7-15(10)	0-7(2)	0
	Down	25-30(30)	10-30(20)	0-10(3)	0
10, 13	Up	8-15(10)	3-8(6)	0-3(1)	0
	Down	10-15(15)	5-10(9)	0-5(2)	0
Medium bulldozers					
1, 2	Up	85-125(110)	60-85(75)	30-60(45)	0-30(6)
	Down	125-145(140)	130-145(145)	75-130(110)	0-75(0)
3, 5, 8	Up	70-105(85)	45-70(55)	15-45(30)	0-15(0)
	Down	105-120(115)	105-120(115)	55-105(85)	0-55(0)
4	Up	35-60(45)	20-35(25)	2-20(10)	0-2(0)
	Down	60-75(70)	65-76(75)	20-65(50)	0-20(0)
6, 7, 9	Up	50-85(70)	30-50(40)	7-30(20)	0-7(0)
	Down	85-100(95)	85-100(100)	40-85(70)	0-40(0)
11, 12	Up	25-40(30)	15-25(20)	1-15(7)	0-1(0)
	Down	40-55(45)	45-55(55)	0-45(35)	0
10, 13	Up	10-20(15)	7-10(8)	0-7(3)	0
	Down	20-25(25)	20-25(25)	0-20(10)	0
Large bulldozers					
1, 2	Up	100-140(120)	70-100(85)	35-70(55)	0-35(10)
	Down	140-155(150)	140-155(155)	85-140(115)	0-85(0)
3, 5, 8	Up	75-110(95)	50-75(60)	20-50(35)	0-20(1)
	Down	110-130(125)	110-130(125)	55-110(85)	0-55(0)
4	Up	45-70(60)	30-45(35)	8-30(20)	0-8(0)
	Down	70-85(80)	75-85(80)	25-75(55)	0-25(0)
6, 7, 9	Up	65-95(80)	40-65(50)	15-40(25)	0-15(0)
	Down	95-110(105)	90-110(105)	50-90(70)	0-50(0)
11, 12	Up	35-55(45)	20-35(25)	3-20(10)	0-3(0)
	Down	55-65(60)	55-65(60)	6-55(40)	0-6(0)
10, 13	Up	20-35(30)	9-20(15)	0-9(4)	0
	Down	35-40(40)	30-40(40)	0-30(15)	0

Rule for using the table: Production rates are not precise but will vary with conditions. The midpoint rates (parentheses) should be used for special studies, such as the USDA Forest Service's fire economics analysis. The higher rate for each set should be used for the following conditions: newer bulldozers (1975 or later model), bulldozers in excellent operating condition, most qualified operators, ambient air temperature of less than 90 °F, moist soil, few or no rocks, no lost time, indirect fireline, average fire behavior, daylight operations, and less resistive vegetative types within each fire behavior fuel model. The lower rate for each set should be used for: older bulldozers (1975 and older), bulldozers in poorer operating condition, poorly qualified operators, air temperature of 90 °F or more, very dry soil, very rocky soil, anticipated lost time, direct fireline, high-intensity fire behavior, night operations, and more resistive vegetative types within each fire behavior fuel model. For combinations of these conditions, use rates somewhere within the range given for each set.

Users of the rates should be mindful of the rule of use at the bottom of table 7 and of the discussion in this publication. The rule reflects what was observed during the verification study, especially in relation to two critical factors: soil and equipment operators. Moist soil which provides good traction may increase midpoint rates by 100 percent or more. In the opposite sense, the presence of large boulders or rock outcrops may decrease the midpoint rates by 60 to 70 percent. Even harmless-appearing flat slate can be a frustrating obstacle to experienced operators; bulldozer blades continuously hang up on flat slate that lies at a slight upward angle opposed to the direction of a bulldozer's travel. Inexperienced operators, observed at least twice during the verification study, produced slow production rates because they either wasted much motion by fighting adverse terrain or vegetation, or they were overly cautious and slow. Other conditions that might cause construction rates to fall into the lowest range of the table, or even lower, are as follows: night operations, poorly maintained equipment, ambient air temperature over 100 °F, a very resistive vegetational type within a given fuel model, time lost to mechanical breakdown or abandoned firelines, or other causes. On the other hand, a superior operator, ambient air temperature in the range of 65 to 85 °F, vegetation that less severely restricts a bulldozer's progress than represented by the fuel model in the table—all these things and others will likely produce rates at or above the highest rate of each range.

To sum up, the bulldozer fireline production rates in table 7 are guides, as the rule states. Those who use the table should understand how the rates were derived and adjust them according to conditions actually encountered on a specific fire.

REFERENCES

Anderson, H. E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

British Columbia Forest Service. 1976. Handbook on use of bulldozers on forest fires. For. Protec. Handb. Victoria, BC. 63 p.

California Division of Forestry. 1967. San Antonio bulldozer test. Sacramento, CA. 45 p.

Deeming, J. E.; Burgan, R. E.; Cohen, J. D. 1977. The National Fire-Danger Rating System - 1978. Gen. Tech. Rep. INT-39. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 63 p.

National Wildfire Coordinating Group. 1980. Fireline handbook. National Wildfire Coordinating Group Handbook 3. Washington, DC.

Phillips, C. B. 1983. Study plan for testing adjusted bulldozer fireline production rates. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 13 p. Unpublished draft.

Phillips, C. B.; Barney, R. J. 1984. Updating bulldozer fireline production rates. Gen. Tech. Rep. INT-166. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 21 p.

Schmidt, G.; Rinehart, G. C. 1982. Line production estimating guides for fire behavior fuel models. Fire Management Notes. Washington, DC: U.S. Department of Agriculture, Forest Service; 43: 3, 6-9.

Steele, R. W. 1961. Use of bulldozers for fireline construction. Bull. 19. Missoula, MT: Montana Forest and Conservation Experiment Station. 11 p.

U.S. Department of Agriculture, Forest Service. 1948. Comparative performance of D-6 and D-7 Caterpillar tractors equipped with hydraulic angle dozers. ED Rep. 13. Arcadia, CA: Arcadia Fire Control Equipment Development Center. 22 p.

U.S. Department of Agriculture, Forest Service. 1973. Fireline handbook. FSH 5109.17. Washington, DC.

U.S. Department of Agriculture, Forest Service. 1980. Fire management analysis and planning handbook. FSH 5109.19, Appendix A, 6-8. Washington, DC. Unpublished draft.

Phillips, Clinton, B.; George, Charles W.; Nelson, David K. 1988. Bulldozer fireline production rates—1988 update. Res. Pap. INT-392. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 13 p.

Presents current (1988) fireline production rates for bulldozers, by size of machine, fuel type, slope, and site conditions. Includes nomograms and a master table for estimating production rates. Describes how data were collected and production rates were calculated.

KEYWORDS: fire management, fire control, prescribed burning, fire technology

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-393

July 1988

Growth of Regeneration Defoliated by Spruce Budworm in Idaho

Dennis E. Ferguson

CLEMSON
NOV 23
PUBL

THE AUTHOR

DENNIS E. FERGUSON is a research forester with the Intermountain Research Station, Moscow, ID. He has worked primarily with predicting establishment of regeneration and growth of young trees in the Northern Rocky Mountains.

RESEARCH SUMMARY

Mathematical equations for predicting growth and development of four conifer species defoliated by western spruce budworm in Idaho are presented. Combinations of regeneration systems, ecological conditions, and defoliation levels were sampled to ensure that equations have broad applicability. A modeling strategy is provided to link these equations to growth and yield models so that short-term and long-term impacts can be assessed.

The research addresses budworm effects on four major features of regeneration development—dieback, height growth, crown ratio, and mortality. Backdating was used to characterize trees at the start of the study, then trees were measured annually for 5 consecutive years. Eleven percent of the host trees had dieback during the 5-year measurement period. The probability of dieback increases with increasing defoliation, increasing tree height, and decreasing crown ratio. The amount of dieback varied from 0.0 to 6.4 feet (0 to 67 percent of tree height). Over the 5-year period, 86 percent of the host trees had positive height growth. Height growth is related to tree and site conditions as well as defoliation level. Both defoliation prior to and during the 5-year period were significant, with increasing defoliation being associated with less height growth. Budworm defoliation prior to the 5-year measurement period decreased crown ratio, but defoliation during the period was not significant. Only 3 percent of the trees died; thus the dataset was not large enough to develop a reliable mortality model. Indications are that small crown ratios or high defoliation levels increase the probability of mortality.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Growth of Regeneration Defoliated by Spruce Budworm in Idaho

Dennis E. Ferguson

INTRODUCTION

Defoliation by the western spruce budworm (*Choristoneura occidentalis* Freeman) affects growth and survival of host trees in western portions of the United States and Canada. Budworm reduces growth, crown volume, and cone crops, and increases top-kill, mortality, deformities, and predisposition to insects and diseases. Impacts of budworm defoliation on large trees have been studied in some detail (see reviews by McKnight 1965 and Johnson and Denton 1975, as well as reports by Ferrell and Scharpf 1982, Van Sickle and others 1983, Swetnam 1983, Beveridge and Cahill 1984, Alfaro and others 1985, and Sanders and others 1985).

Regeneration is also fed upon by western spruce budworm, but fewer studies have reported budworm effects on regeneration. Small trees have a greater proportion of current-year foliage than large trees, can have small crown ratios if growing as understory trees, and may receive a disproportionate amount of budworm dispersing from overstory trees (Johnson and Denton 1975). Understory regeneration is often defoliated sooner than larger trees. Conversely, regeneration growing in young, even-age stands, without nearby overstory trees, is minimally fed upon by budworm (Carlson and others 1985).

The study reported here was designed to quantify impacts of western spruce budworm feeding on host regeneration up to 3.0 inches diameter at breast height (d.b.h.). The primary objective was to develop mathematical equations predicting 5-year periodic height growth of host regeneration as a function of species, tree condition, site/stand characteristics, and budworm defoliation. Additional information was gathered on dieback, mortality, and changes in crown ratio. Results apply to four species of host regeneration in budworm outbreak areas in Idaho. Host species are Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.), Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). Questions regarding the probability of regeneration being defoliated by budworm are not addressed by this study.

STUDY DESIGN

Height growth of small trees can be backdated by measuring the height increment indicated by branch whorls. Often, this is not possible when growth is altered by budworm feeding. Top dieback and destroyed terminals being replaced by lateral branches can make it impossible to retrospectively determine height increments. Defoliation is difficult to backdate beyond a few years because branching pattern is abnormal and entire cohorts of needles may be missing. Therefore, this study was designed to follow growth and defoliation concurrently, although some backdating would be necessary to characterize the tree at the beginning of the study period.

Data were collected so that predictive equations would apply to a wide range of ecological conditions, defoliation levels, and current cultural practices. Active budworm outbreak areas were visited to establish semipermanent plots having combinations of ecology, defoliation, and silviculture of interest. Stands were selected by qualified research silviculturists using the following guidelines:

1. The stand was a relatively homogeneous area of at least 1 acre on which host regeneration up to 3.0 inches d.b.h. was established.
2. The last disturbance to the stand was at least 5 years ago. This 5-year period allows trees to adjust to changes in conditions caused by prior disturbances.
3. The stand was in a current budworm outbreak area. Defoliation levels by stand and by trees within stands were often quite variable.
4. With one geographic area (a Ranger District), stands were chosen to differ in such things as habitat type, host species, tree sizes, aspect, overstory density, or infestation level. This helped ensure dispersal of sampled conditions.

Extensive measurements were recorded in stands as of the beginning and end of a 5-year period. In addition, the stands were visited each fall to record current-year defoliation, height growth, and mortality. Variables recorded and timing of measurements are summarized in table 1. Plot installation began in the summer of 1979. Conditions as of the spring of 1978 were backdated by recording defoliation as of 1 year ago, height as of 1 year ago, and so on. Thus 5 years of information was gathered during four field seasons.

Ten-point clusters were used to sample stands. Each point is the center of a 1/300-acre circular fixed area plot and the center for a horizontal point sample. In stands with an overstory, basal area factors of 10, 20, or 40 ft^2/acre/tree were used to sample about five to seven overstory trees per point. Basal area factors were not changed between points within a stand.

The 1/300-acre plot was used to sample trees less than 3.0 inches d.b.h. and assess competition from shrubs, forbs, and grasses. All established conifers on this plot were recorded. Minimum establishment heights were

Table 1—Variables and frequency of measurement for three tree size classes. The 1978 measurements were recorded as the plots were installed prior to August 1979

Variable	Tree size class (d.b.h.) 0-2.9 inches	3.0-4.9 inches	≥5.0 inches	Year(s) recorded 1978	1979	1980	1981	1982
Identification field	x	x	x	√	√	√	√	√
Best tree	x			√				
Advance/subsequent	x			√				
Crown class relative to:								
A trees	x	x	x	√				√
B shrubs	x			√				√
Excess tree count	x			√				√
Yearly height increment	x			√	√	√	√	√
Current height	x	x	x	√				√
Height to dead or broken top	x	x	x	√	√	√	√	√
Crown dimensions	x	x		√				√
Vigor rating	x	x	x	√				√
D.b.h.	x	x	x		√			√
Dead/alive	x	x	x		√	√	√	√
Defoliation by crown thirds	x	x	x	√	√	√	√	√
Other:								
shrubs, forbs, grasses				√				√
damage/diseases	x	x	x	√	√	√	√	√
increment cores		x	x					√

0.5 ft tall for shade-tolerant species and 1.0 ft tall for shade-intolerant species. A subsample of "best trees" was selected on each plot, using the following set of rules:

1. Select the two trees most likely to survive and grow well, regardless of species.
2. Of each additional species, select one tree that is most likely to survive and grow well.
3. If rules 1 and 2 do not result in at least four trees, reselect from the remaining trees until four are selected, or until all trees have been considered.

Best trees were the sampling unit for this study. These trees were the most likely to produce a product later in the rotation. Sampling at least one tree of each species allowed for different growth rates among species as trees differentiate into crown classes. Sampling one tree of each species also meant that the best available host trees were included in the sample.

Best trees were tagged and measured for height (nearest 0.1 ft), height to dead or broken top (0.1 ft), crown dimensions (0.1 ft), d.b.h. (0.1 inch), crown class relative to (a) trees and (b) shrubs, advance or subsequent germination status relative to last stand disturbance, mortality, damages/diseases, height increments (0.01 ft), and ocular estimates of current-year defoliation.

Current-year defoliation was recorded each fall for best trees and tagged trees in the horizontal point sample. Crowns were divided into thirds—upper, middle, and lower—with the terminal rated separately for best trees. Binoculars were used to aid estimates in crowns of overstory trees. Defoliation was determined by ocularly estimating the proportion of current-year needles destroyed by budworm feeding. Estimates were rounded to the nearest 10 percent. Defoliation on each third of the crown was evaluated retrospectively for 1976, 1977, and 1978. Defoliation and height growth were estimated each fall in the years 1979, 1980, 1981, and 1982.

Regeneration not chosen as best trees was called "excess" trees and was counted by species and 1-ft height classes. Shrubs, forbs, and grasses were characterized by recording average height and percentage of plot coverage for species covering at least 5 percent of the plot.

Trees in the horizontal point sample were tagged and measured for height, crown class, height to dead or broken top, crown ratio, mortality, and defoliation by crown thirds. These trees characterize the effect of overstory competition on growth of regeneration. Diameter at breast height was recorded in the fall of 1979 and 1982, and increment cores were extracted in the fall of 1982. Results of analysis of large trees will be published separately.

Stand variables include geographic location, aspect, slope percent, elevation, topographic position, and habitat type. Habitat type references used were Cooper and others (1987) for northern Idaho, Steele and others (1981) for central Idaho, and Steele and others (1983) for eastern Idaho.

Ten-point clusters were installed in 64 stands (fig. 1). Stands in northern Idaho were clustered in areas near Avery and Powell. The outbreak in central Idaho covered a wider geographic area, allowing better distribution of sample stands. In 1979 few Douglas-fir climax stands could be found having the necessary combinations of silviculture, host trees, and defoliation. For this reason, five moderately to heavily defoliated stands were sampled in eastern Idaho. Table 2 shows the number of stands by regeneration system and overstory climax series (the most

Figure 1—Study site location for 64 sample stands.

Table 2 —Number of stands sampled by overstory climax series and regeneration method. Each stand contains data from a cluster of ten 1/300-acre plots, with corresponding horizontal point sample of the overstory

Overstory climax series	Regeneration method	Number of stands
Douglas-fir	clearcut/seedtree	4
	shelterwood/selection	3
Grand fir and redcedar (*Thuja plicata* Donn. ex D. Don)	clearcut/seedtree	14
	shelterwood/selection	9
Subalpine fir	clearcut/seedtree	18
	shelterwood/selection	16
Total		64

Table 3—Attributes of 64 stands sampled for impacts by western spruce budworm on host regeneration

Attribute	Unit of measure	Mean	Standard deviation	Extreme values
Elevation	Nearest 100 feet	52.4	8.3	37.0 to 76.0
Aspect	Degrees	187	114	0 to 360
Slope	Percent	35.6	19.1	0.0 to 70.0
Overstory density	Ft^2/acre at breast height	44.0	43.3	0.0 to 236.0

shade-tolerant conifer able to maintain a self-reproducing population; Daubenmire 1966). Table 3 shows additional attributes of the 64 sample stands.

Douglas-fir, grand fir, Engelmann spruce, and subalpine fir are the primary species fed upon in these stands. Western larch (*Larix occidentalis* Nutt.) is also a host species, but few trees were found in the sample stands. On larch, budworm severs terminal leaders and lateral branches; thus one budworm can have a large impact. On species other than larch, budworms mainly feed on new needles and buds, and the impact of individual worms is much less (Fellin and Schmidt 1967; Schmidt and Fellin 1973).

MODELING TECHNIQUE

This study quantified four major impacts to host regeneration:

1. Probability of dieback (zero or negative 5-year growth).
2. Amount of dieback.
3. Five-year periodic height increment.
4. Crown ratio changes.

The term "dieback" refers to top-kill from which trees can recover to produce a merchantable product above the point of top-kill. "Top-kill," as used in the Prognosis Model (Wykoff 1986), refers to a truncated height above which no merchantable volume will accrue.

Information collected on mortality is discussed, but more data are needed to develop a predictive model.

Equations quantifying these impacts will be used in the Budworm Prognosis Model (Crookston 1985). A diagram of one Budworm Prognosis Model cycle is presented in figure 2. Each cycle accounts for growth and dieback. Crown ratios also change, partly the result of budworm defoliation. The new crown ratio represents an index of vigor carried over to the next projection cycle.

Equations were developed using REX, a linear regression package (Grosenbaugh 1967) and RISK, a nonlinear regression algorithm (Hamilton 1974). RISK is an algorithm for dichotomously distributed dependent variables (for example, a tree did or did not have dieback). The form of the equation for RISK is

$$P = (1 + e^{-(\Sigma B_i X_i)})^{-1} \quad (1)$$

Probability (P) is continuous and bounded within the interval [0,1]. Goodness of fit for coefficients in linear and nonlinear equations was evaluated at the 0.05 significance level.

A 1-year delay was hypothesized between defoliation and its impact on regeneration height growth. This delay was based on knowledge that height growth of species with predetermined buds is correlated with conditions existent during bud formation (Kozlowski 1964) and that photosynthates for terminal bud expansion come mainly from 1-year-old foliage (Kozlowski and Winget 1964). Preliminary equations were tested using a 1-year delay versus no delay, and no differences were apparent. Because budworms feed on current-year terminal buds and terminal leaders, a delayed effect of defoliation may be masked. Independent variables representing defoliation are averages with no delay assumed between defoliation and impact on growth. Two averages were calculated—one for the 5-year measurement period of this study (1978 through 1982), and one for the 2-year period prior to the study period (1976 and 1977).

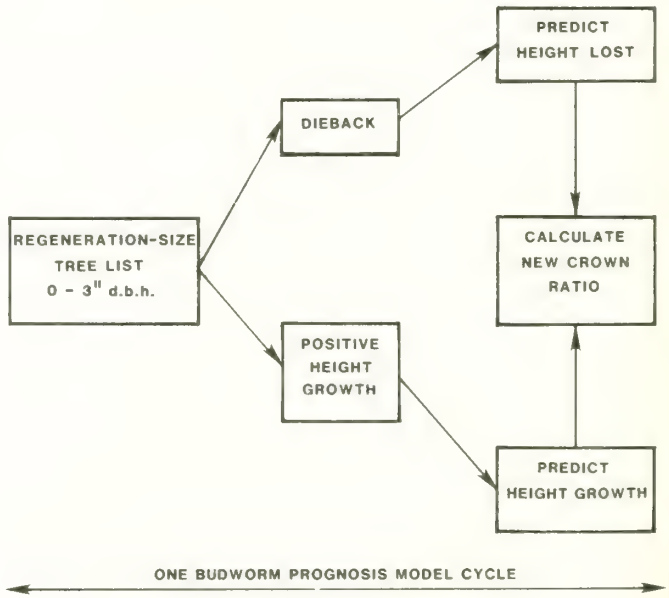


Figure 2—Diagram of steps to process regeneration for one cycle in the Budworm Prognosis Model.

Table 4—Attributes of sample trees by species and status at end of sampling period

Species	Number of trees	Beginning height (ft) Mean	Min-max values	Height increment (ft) Mean	Min-max values	5-year defoliation (percent) Mean	Min-max values	Beginning crown ratio Mean	Min-Max values
Status: Positive 5-year height increment									
Douglas-fir	215	5.0	0.1 to 23.2	1.5	0.1 to 7.7	19.9	0.0 to 85.3	0.58	0.03 to 1.00
Grand fir	444	4.2	.5 to 16.5	1.3	.1 to 8.8	19.3	.0 to 99.3	.55	.05 to .96
Engelmann spruce	157	4.1	.6 to 14.0	1.7	.1 to 7.1	12.8	.0 to 82.0	.66	.15 to .98
Subalpine fir	205	4.9	.5 to 16.8	1.8	.1 to 7.8	15.4	.0 to 84.0	.64	.12 to 1.00
Total	1,021								
Status: Zero or negative 5-year height increment									
Douglas-fir	37	7.0	1.0 to 18.0	–.4	–3.0 to .0	30.6	.0 to 92.0	.47	.08 to 0.94
Grand fir	55	6.6	.7 to 30.0	–.5	–5.0 to .0	44.1	.0 to 92.7	.45	.18 to .78
Engelmann spruce	9	5.6	1.5 to 11.9	–.3	–1.0 to .0	27.0	2.0 to 79.3	.49	.24 to .82
Subalpine fir	26	5.6	1.1 to 11.4	–.6	–6.4 to .0	56.6	11.3 to 95.3	.55	.14 to .96
Total	127								
Status: Dead at end of 5-year measurement period									
Douglas-fir	12	6.3	1.3 to 11.0			18.8	.0 to 85.3	.48	.11 to 0.76
Grand fir	11	2.8	.5 to 7.3			25.0	.7 to 96.7	.42	.14 to .68
Engelmann spruce	5	9.8	4.2 to 18.0			22.5	.7 to 83.7	.36	.28 to .48
Subalpine fir	7	6.7	2.5 to 15.5			42.5	.0 to 93.3	.46	.29 to .62
Total	35								
Grand total	1,183								

Defoliation estimates were backdated for the years 1976, 1977, and 1978. These estimates were recorded during the summer of 1979 as plots were being installed. It is possible that estimates of backdated defoliation could differ from the estimates made at the end of each growing season in 1979 through 1982. Variation, by species, between the backdated estimates and the current-year estimates was compared. The standard deviation of mean annual defoliation ratio for backdated estimates varied from 0.20 to 0.33 and averaged 0.27 for 12 observations (four host species times 3 years). The standard deviation for current-year estimates varied from 0.19 to 0.35, averaging 0.27 for 16 observations (four host species times 4 years). Thus, the backdated estimates are consistent with the prospective estimates. Backdating defoliation 3 years seems acceptable, considering that the 3-year period is less than the number of years of needle retention for these species, and field crews could get close to regeneration-size trees to accurately examine the cohorts of needles.

RESULTS AND DISCUSSION

A total of 1,183 host trees were measured for the entire 5-year period of this study. Of these, 127 trees (11 percent) suffered dieback and 35 (3 percent) died. Table 4 summarizes statistics for best trees by status at the end of the 5-year measurement period. These data are characterized by a wide range of values for the attributes shown. Compared to trees having positive growth, trees with dieback tended to be taller, had more defoliation over the 5-year period, and had smaller beginning crown ratios. This trend is also true of the 35 trees that died.

Trees were categorized by their status at the end of the 5-year measurement period—those having positive height increment, those having dieback, and those that died. Regression equations were then developed by status. Definitions for dependent and independent variables used in the regression equations are given in table 5.

Probability of Dieback

Dieback is defined as trees having zero or negative height increment for the 5-year period of this study. The event of dieback is distributed dichotomously; that is, a tree had dieback or it did not. All trees alive at the end of 5 years were used for this analysis, and RISK was used to estimate coefficients for the probability of dieback. Table 6 lists the coefficients and figure 3 shows comparative curves for various tree and defoliation conditions.

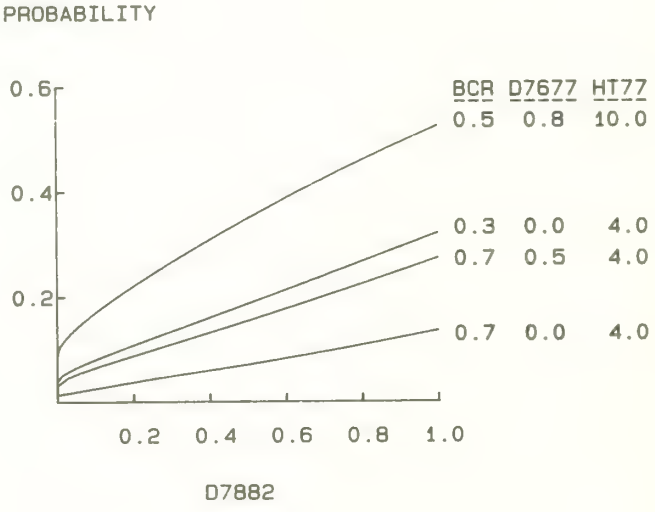
Important predictors of dieback are defoliation prior to and during the measurement period, beginning crown ratio, and beginning height. Defoliation during the 5-year period increased the probability of dieback more than defoliation prior to the period, although both are significant at the 5 percent level. Taller trees and those with smaller crown ratios have greater odds of sustaining dieback. There were not significant differences among the four species. Also crown class was not important when included in addition to the independent variables shown in table 6.

Table 5—Explanation of variables used in developing equations

Variable	Definition
BCR	Beginning crown ratio, measured during the summer of 1979.
D7677	Average defoliation ratio of current-year foliage for 1976 and 1977 (defoliation prior to measurement period).
D7882	Average defoliation ratio of current-year foliage for 1978 through 1982 (defoliation during the measurement period).
HT77	Tree height (ft) in the fall of 1977 (beginning tree height).
HT82	Tree height (ft) in the fall of 1982 (ending tree height).
BA	Overstory basal area in the fall of 1982 (ft^2/acre at breast height).
ASP	Aspect in radians.
SLO	Slope tangent (slope percent divided by 100).
ELEV	Elevation above sea level to the nearest hundred feet, for example, 35 = 3,500 feet.
TPP	Number of trees less than 3.0 inches d.b.h. on the fixed plot.
DBH82	Tree d.b.h. in the fall of 1982.
ADVANCE	Class variable for advance regeneration ADVANCE = 1.0 if the tree is older than the last stand disturbance; 0.0 if the tree is not advance.
DIEBACK	Class variable for trees having zero or negative net height increment over the 5-year measurement period.
HTI	Positive 5-year periodic height increment (ft).
CR	Ending crown ratio, measured in the fall of 1982.
CROWN CLASSES	
DOMINANT	Crown receiving sunlight from above and three or four sides.
CODOMINANT	Crown receiving sunlight from above and one or two sides.
INTERMEDIATE	Crown receiving sunlight only from above.
SUPPRESSED	Crown not receiving sunlight from above or sides.
SPECIES	
ABGR	*Abies grandis*
ABLA	*Abies lasiocarpa*
ACGL	*Acer glabrum*
CLUN	*Clintonia uniflora*
MEFE	*Menziesia ferruginea*
PSME	*Pseudotsuga menziesii*
SPBE	*Spiraea betulifolia*
THPL	*Thuja plicata*
VAGL	*Vaccinium globulare*
VASC	*Vaccinium scoparium*
XETE	*Xerophyllum tenax*

Table 6—Coefficients for equation predicting the probability of dieback (P) for budworm defoliated regeneration. Form of the equation is $P = [1 + e^{-(\Sigma \beta_i X_i)}]^{-1}$. The t-ratios for all coefficients were significant at the 5 percent level

Variable (X)	Coefficient (β)
β_0	–2.5817
BCR	–2.7635
$\sqrt{D7677}$	1.2394
$\sqrt{D7882}$	2.4696
HT77	.0488



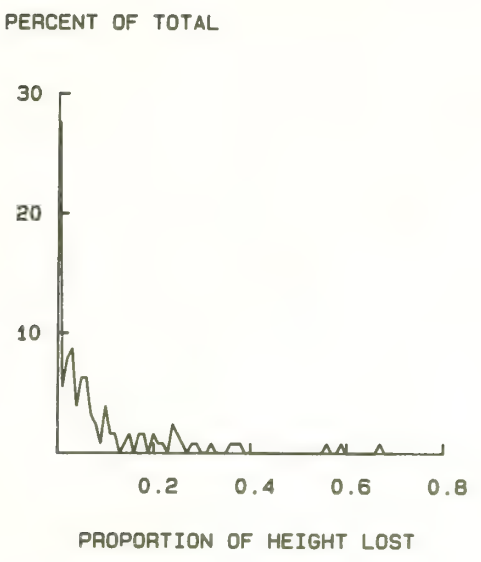


Figure 4—Distribution of the proportion of height lost for trees having dieback. Proportion = length of dieback ÷ beginning tree height.

Amount of Dieback

Using the 127 trees that had dieback, combinations of dependent and independent variables were explored to predict the amount of height loss. Dependent variables included length of top-kill, proportion of height lost, and proportion of crown ratio lost. The only significant independent variables in these linear regression equations were tree height, crown length, and slope, but their predictive value was very low.

Part of the problem in predicting the amount of dieback is that the loss is only a "snapshot" at one particular time during an ongoing infestation. Dieback could increase or decrease, depending on current and future defoliation levels.

Another explanation is found in the frequency distribution of the proportion of height loss shown in figure 4. Most of the trees had no net loss over the 5-year period. These trees are followed in frequency by fewer and fewer trees with increasing losses. Regression equations tend to predict near the mean loss, resulting in large errors of prediction.

Because the amount of dieback is highly variable, effort was directed toward quantifying the distribution associated with the loss. A Weibull function (Bailey and Dell 1973) was fit to the data points of figure 4. The cumulative distribution function (*CDF*) is

$$CDF = 1 - e^{-[(PD/5.684)^{0.587}]} \qquad (2)$$

where *PD* is proportion of total tree height lost to dieback.

In a growth and yield simulation where growth projections are made for individual trees, the equation shown in table 6 is used to determine which trees lose tops. For each tree having dieback, a uniformly distributed random number is chosen in the interval [0,1] and substituted for *CDF* in equation (2). The equation is then solved for *PD*, the proportion of dieback. The simulated distribution approximates the actual distribution, given that enough trees are in the inventory. The Prognosis Model (Stage 1973) ensures an adequate number of trees by replicating tree records.

Height Growth

Overall, 1,021 (86 percent) of the sample trees had positive height increments as determined by subtracting height in 1977 from height in 1982. Although yearly increments had been recorded, it was not accurate to sum these over the 5 years because lateral branches often turned up to replace shorter, defoliated terminal shoots. When lateral branches replace terminals, tree height can increase even when defoliation is quite heavy.

The four species were analyzed separately. Important independent variables were identified through screening analysis using REX. Likely transformations of independent and dependent variables were explored. The shape of the response surface for defoliation was examined by dividing defoliation into discrete groups (0 to 5 percent, 5 to 15.5 percent, 15.5 to 26.5 percent, ..., 56.6 to 65.5 percent, and ≥65.5 percent) to be used as class variables. A coefficient was estimated for each class while using the most important tree, site, and stand conditions as covariates. The results were plotted and are shown in figure 5. The response surface for regression coefficients is linear and negative when plotted on the log scale.

Final equations were developed after including species-specific effects such as habitat type, geographic location, or elevation (table 7). The form of the equation is

$$\ln(HTI) = B_0 + B_1X_1 + B_2X_2 + \ldots + B_iX_i \qquad (3)$$

where

HTI = 5-year height increment
B_i = regression coefficients
X_i = independent variables.

This equation form was the best transformation found when screening the data and has been used in predicting regeneration height growth by Wykoff and others (1982). The effect of defoliation is shown graphically in figure 6.

Taller trees and those with larger crown ratios grow better than shorter trees or those with smaller crown ratios. Both defoliation prior to and during the growth period significantly reduce height growth of regeneration-size trees, but the current defoliation has a greater effect. Increasing overstory basal area reduced expected height increment, and the reduction is greater for the moderately shade-tolerant Douglas-fir and Engelmann spruce than it is for shade-tolerant grand fir and subalpine fir.

Crown Ratio

Crown ratio is an indicator of tree vigor because it indexes the amount of foliage available to produce photosynthates. Spruce budworm defoliation reduces the foliage density and crown ratio which, in turn, impact future

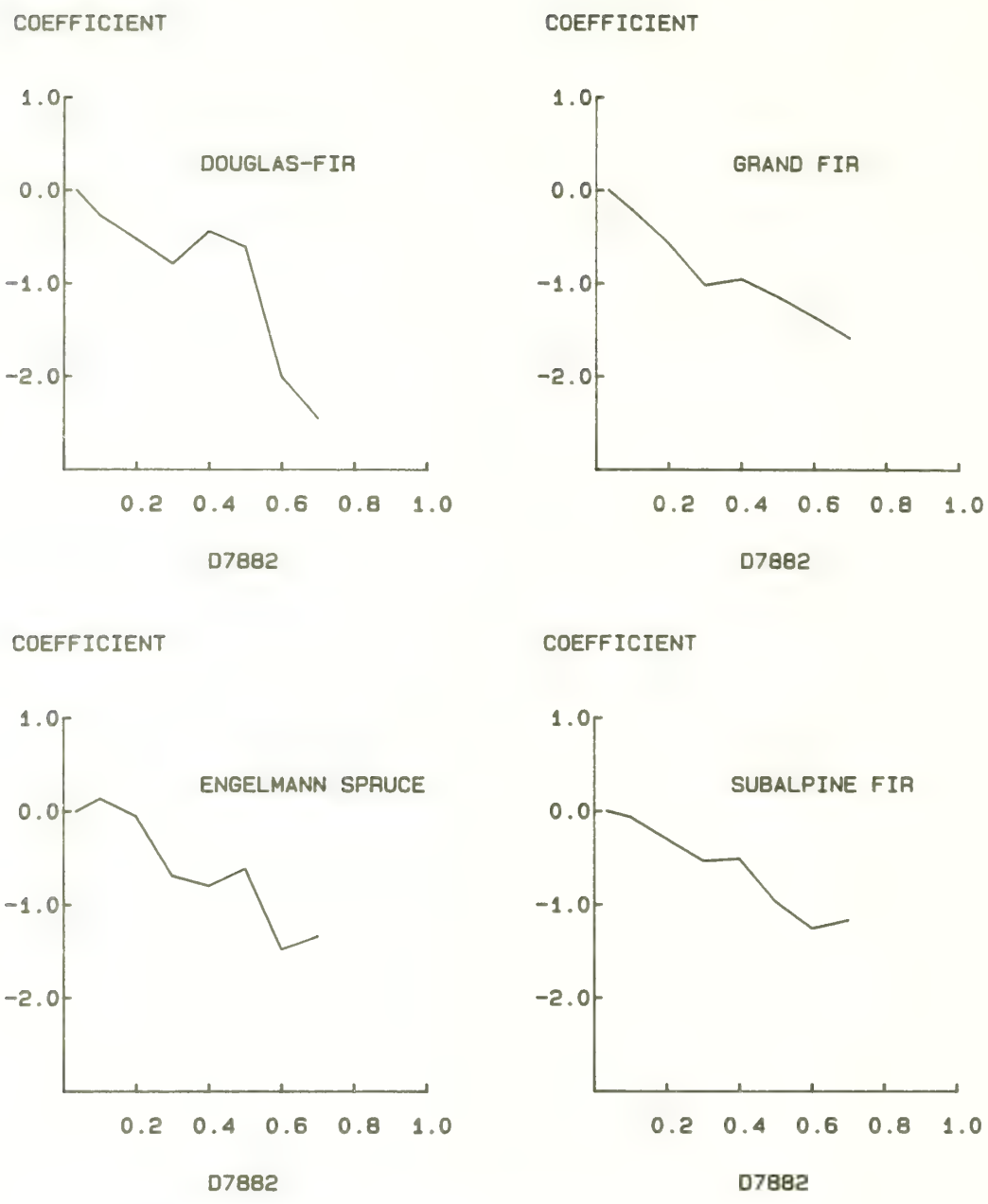


Figure 5—Regression coefficients predicting height growth by defoliation class and species. Results are linear when plotted on the natural logarithmic scale.

Table 7—Coefficients for equations predicting height increment (HTI) for 1,021 trees having positive height increments over the 5-year period. The form of the equation is $\ln(HTI) = \Sigma\beta_i X_i$. Equations are for trees up to 3.0 inches d.b.h.

Variable (X)	Douglas-fir (β)	Grand fir (β)	Engelmann spruce (β)	Subalpine fir (β)
β_0	0.1137	1.1714	−2.3558	−1.1306
ln(HT77)	.5991	.5173	.5610	.7452
BCR	1.6987	1.7175	1.7423	.8682
ln(BA)	−.1150	−.0428	−.1415	−.0709
D7882	−1.5133	−1.3745	−1.8405	−1.4359
D7677	−.9624	−.6263	−1.0766	−.9302
COS(ASP)*SLO	.4544	−.0152		
SIN(ASP)*SLO	.3995	.2820		
SLO	−.0506	.7228		.7320
ELEV	−.0207	−.0165	.0241	
ADVANCE		−.1948		
FORESTS				
PAYETTE		.5981	.2410	
BOISE		.8354	.9165	
PANHANDLE		.0	.2410	
CLEARWATER		.0	.0	
TARGHEE		[1]	[1]	[1]
HABITAT TYPES				
PSME series		[1]	[1]	[1]
ABGR/SPBE		−.5965	[1]	
ABGR/VAGL		−.5965	−.5558	[1]
ABGR/CLUN		.0	.0	
ABGR/ACGL		−.5965	[1]	[1]
THPL/CLUN		.0	.0	
ABLA/CLUN		.0	.0	
ABLA/MEFE		−.5965	−.5558	
ABLA/XETE		−.5965	−.5558	
ABLA/VAGL		−.5965	−.5558	
ABLA/VASC		−.5965	−.5558	
CROWN CLASS				
DOMINANT		.6485	.2714	
CODOMINANT		.5588	.1084	
INTERMEDIATE		.4750	.0	
SUPPRESSED		.0	.0	
No. of trees	215	444	157	205
r^2	0.5204	0.5979	.6631	0.6451
Standard error of estimate	.8193	.6495	.5708	.6671

[1]No data for this cell.

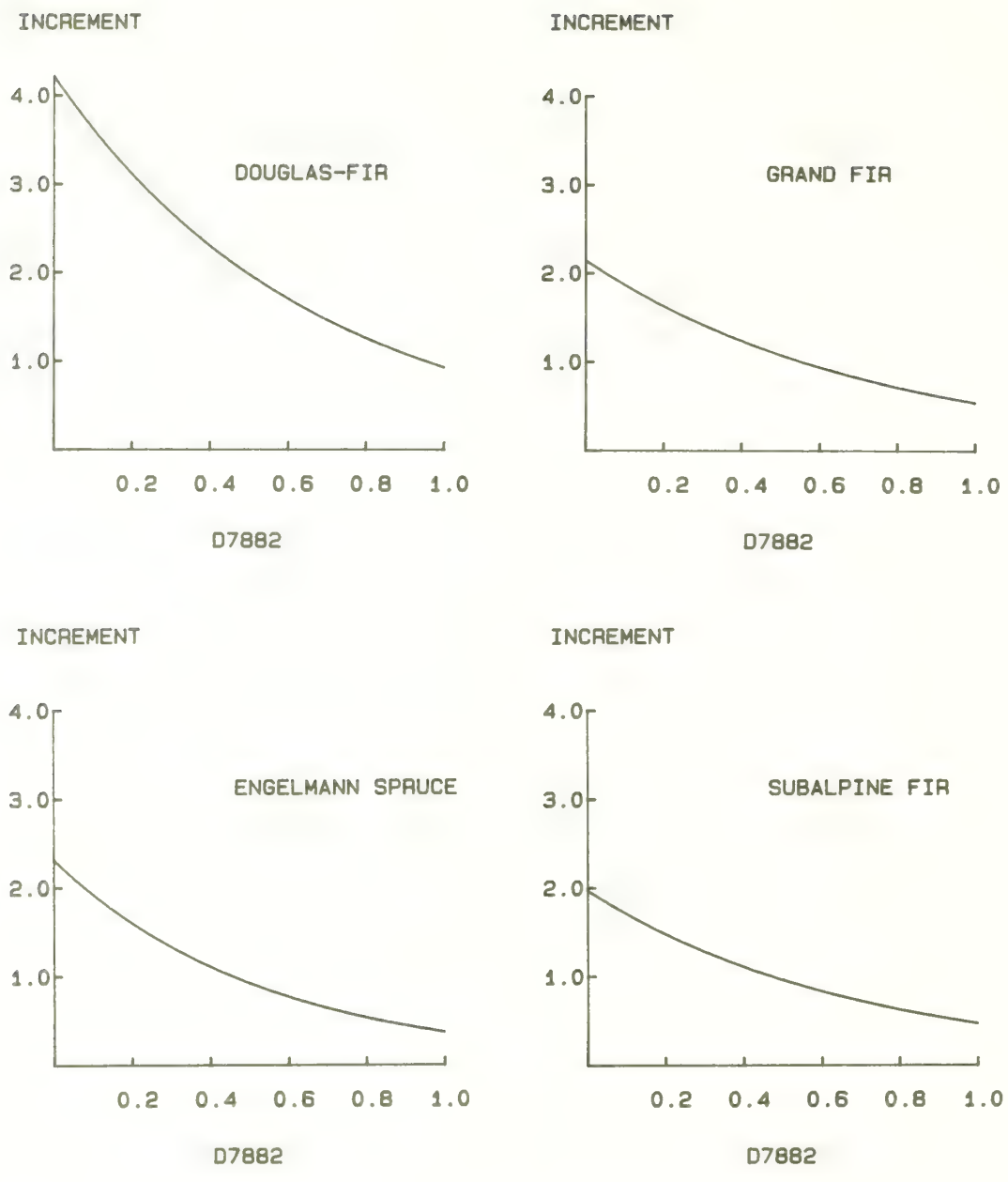


Figure 6—Predicted 5-year height increment (feet) as a function of 5-year defoliation and species. Graphs were developed using the equations shown in table 7. Variables held constant in the equations are HT77 = 5.0, BCR = 0.7, BA = 1.0, D7677 = 0.0, ASP = 0.0, SLO = 0.0, ELEV = 40.0, ADVANCE = 0.0, Clearwater National Forest, THPL/CLUN habitat type, and codominant crown class.

Table 8—Coefficients for equations predicting crown ratio (CR) at the end of the 5-year measurement period. Equations are for trees with positive height growth and those suffering dieback. The form of the equation is shown in equation 4

Variable X	Douglas-fir (β)	Grand fir (β)	Engelmann spruce (β)	Subalpine fir (β)
β_0	−1.2675	−0.7396	−1.1142	−0.9827
ln(HT82)	.1615	.3353	.4405	
ln(BA)	−.1085	−.0408	−.1084	
COS(ASP)*SLO	−.4233			.6411
SIN(ASP)*SLO	.1974			−.3264
SLO	.4292			.3482
D7677	−.5402	−.6442	−.8326	−.6892
ln(TPP)		−.1059		
BCR	2.4368	2.4586	2.8443	2.8178
ADVANCE		−.2473	−.2693	
CROWN CLASS				
DOMINANT	.8636	.4688		.6417
CODOMINANT	.6543	.4304		.2698
INTERMEDIATE	.4419	.3436		.3377
SUPPRESSED	.0	.0		.0
DIEBACK		−.3766		−.3551
No. of trees	252	499	166	231
r^2	.6104	.5780	.5874	.6006
Standard error of estimate	.6152	.6327	.6289	.6935

growth, dieback, and mortality. When estimating crown ratios, field crews made ocular adjustments for trees having one-sided crowns or missing portions of crowns, but no adjustments were made for the sparseness of crowns caused by defoliation. Thus crown ratio is that proportion of tree height that would refoliate if budworm feeding stopped.

Equations were developed to predict crown ratio at the end of the measurement period. The form of the equation is

$$CR = [1 + e^{-(\Sigma B_i X_i)}]^{-1} \quad (4)$$

where

CR = crown ratio
B_i = regression coefficients
X_i = independent variables,

which is a sigmoid-shape curve bounded within the interval [0,1]. Coefficients are shown in table 8. The most important variables are crown ratio at the beginning of the period, defoliation prior to the beginning of the measurement period, overstory basal area, tree size, and crown class in relation to other trees. Trees with larger beginning crown ratios had larger ending crown ratios, but prior budworm defoliation decreased crown ratios. Increasing overstory basal area decreased crown ratios, and larger trees had larger crown ratios. Also, the more dominant the tree relative to other trees, the larger the crown ratio. Defoliation during the measurement period was not significant, indicating a delay between defoliation and reduction in crown ratio. Geographic area, habitat type, and crown class in relation to shrubs were not significant.

Mortality

Only 3 percent of the trees died during the 5-year measurement period of this study. The dataset is too small to develop a reliable equation predicting the probability of mortality, but single independent variable equations were fit to the data using RISK. Crown ratio at the beginning of the measurement period was a significant variable. Trees with small crown ratios have a higher probability of mortality. Defoliation prior to the measurement period was also significant, with increasing defoliation causing increasing mortality. Defoliation during the 5-year period was not significant. A delay between defoliation and mortality has been described by others (Beveridge and Cahill 1984; McLintock 1955).

SUMMARY

This study was undertaken to quantify the impacts of western spruce budworm defoliation on growth and development of young conifers. Equations presented in this paper can be embedded in the Budworm Prognosis Model (Crookston 1985) or other growth and yield simulation models. Through use of simulation models, alternative management prescriptions can be compared.

This study has quantified four major effects of budworm defoliation on regeneration: (1) probability of dieback, (2) amount of dieback, (3) 5-year periodic height increment, and (4) changes in crown ratio.

The probability of dieback increases with increasing defoliation, smaller beginning crown ratios, and increasing tree size. Still, only 11 percent of host regeneration had dieback. Even with heavy defoliation, lateral branches or buds replace terminal shoots destroyed by budworm and, as shown in figure 4, the proportion of height lost is usually low.

Periodic height increment is also reduced by budworm feeding. Defoliation prior to and during the growth period significantly reduces predicted 5-year height increment. Crown ratio is important in that trees with small crowns grow less and, as shown in the crown ratio equations, budworm feeding has a delayed effect on reducing the crown ratio of defoliated trees.

Defoliation prior to the 5-year measurement period is a good predictor of crown ratio at the end of the period. Increasing defoliation prior to the growth period results in smaller crowns, but defoliation during the growth period is not significant.

Few host trees died during the 5-year period of this study. Mortality increases as crown ratio decreases or prior defoliation increases, but the dataset was not large enough to develop a reliable equation.

Several equations in this paper use crown class to help predict growth and development of regeneration. These discrete classes would be appropriate for short-term projections in growth and yield simulations where the list of trees is from a stand inventory. But information is lacking on movement of trees from one class to another as the stand develops and trees differentiate over time. Discrete classes can also produce irregular growth rates as trees pass from one crown class to another. A surrogate is needed to represent the effect of crown class for regeneration-size trees.

REFERENCES

Alfaro, R. I.; Thomson, A. J.; Van Sickle, G. A. 1985. Quantification of Douglas-fir growth losses caused by western spruce budworm defoliation using stem analysis. Canadian Journal of Forest Research. 15: 5-9.

Bailey, R. L.; Dell, T. R. 1973. Quantifying diameter distributions with the Weibull function. Forest Science. 19: 97-104.

Beveridge, R. L.; Cahill, D. B. 1984. Western spruce budworm feeding effects on conifers located on the Boise and Payette National Forests. Forest Pest Management Report 84-7. Boise, ID: U.S. Department of Agriculture, Forest Service. 32 p.

Carlson, C. E.; Fellin, D. G.; Schmidt, W. C.; Wulf, N. W. 1985. Silvicultural approaches to western spruce budworm management in the northern U.S. Rocky Mountains. In: Sanders, C. J.; Stark, R. W.; Mullins, E. J.; Murphy, J., eds. Recent advances in spruce budworms research: Proceedings of the CANUSA spruce budworms research symposium; 1984 September 16-20; Bangor, ME. Ottawa, ON: Canadian Forestry Service: 281-300.

Cooper, S. V.; Neiman, K. E.; Steele, R.; Roberts, D. W. 1987. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. INT-236. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 135 p.

Crookston, N. L. 1985. Forecasting growth and yield of budworm-infested forests. Part II: Western North America and summary. In: Sanders, C. J.; Stark, R. W.; Mullins, E. J.; Murphy, J., eds. Recent advances in spruce budworms research: Proceedings of the CANUSA spruce budworms research symposium; 1984 September 16-20; Bangor, ME. Ottawa, ON: Canadian Forestry Service: 214-230.

Daubenmire, R. 1966. Vegetation: identification of typal communities. Science. 151: 291-298.

Fellin, D. G.; Schmidt, W. C. 1967. Spruce budworm larvae sever stems of western larch shoots in Montana. Journal of Forestry. 65: 258-260.

Ferrell, G. T.; Scharpf, R. F. 1982. Stem volume losses in grand firs topkilled by western spruce budworm in Idaho. Res. Pap. PSW-164. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 10 p.

Grosenbaugh, L. R. 1967. REX—FORTRAN-4 system for combinatorial screening or conventional analysis of multivariate regressions. Res. Pap. PSW-44. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 47 p.

Hamilton, D. A., Jr. 1974. Event probabilities estimated by regression. Res. Pap. INT-152. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 19 p.

Johnson, P. C.; Denton, R. E. 1975. Outbreaks of the western spruce budworm in the American northern Rocky Mountain area from 1922 through 1971. Gen. Tech. Rep. INT-20. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 144 p.

Kozlowski, T. T. 1964. Shoot growth in woody plants. Botanical Review. 30: 335-392.

Kozlowski, T. T.; Winget, C. H. 1964. Contributions of various plant parts to growth of pine shoots. For. Res. Note 113. Madison, WI: University of Wisconsin. 4 p.

McKnight, M. E. 1965. A review of the literature on the spruce budworm, *Choristoneura fumiferana* (Clemens). Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 131 p.

McLintock, T. F. 1955. How damage to balsam fir develops after a spruce budworm epidemic. Stn. Pap. 75. Upper Darby [Broomall], PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 18 p.

Sanders, C. J.; Stark, R. W.; Mullins, E. J.; Murphy, J., eds. 1985. Recent advances in spruce budworms research: Proceedings of the CANUSA spruce budworms research symposium; 1984 September 16-20; Bangor, ME. Ottawa, ON: Canadian Forestry Service. 527 p.

Schmidt, W. C.; Fellin, D. G. 1973. Western spruce budworm damage affects form and height growth of western larch. Canadian Journal of Forest Research. 3: 17-26.

Stage, A. R. 1973. Prognosis Model for stand development. Res. Pap. INT-137. Ogden, UT: U.S. Department of

Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 32 p.

Steele, R.; Cooper, S. V.; Ondov, D. M.; Roberts, D. W.; Pfister, R. D. 1983. Forest habitat types of eastern Idaho-western Wyoming. Gen. Tech. Rep. INT-144. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 122 p.

Steele, R.; Pfister, R. D.; Ryker, R. A.; Kittams, J. A. 1981. Forest habitat types of central Idaho. Gen. Tech. Rep. INT-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 138 p.

Swetnam, T. W. 1983. Radial growth assessment of western spruce budworm infested Douglas-fir trees on the Carson National Forest, New Mexico. Tucson, AZ: University of Arizona, Laboratory of Tree-Ring Research. 28 p.

Van Sickle, G. A.; Alfaro, R. I.; Thomson, A. J. 1983. Douglas-fir height growth affected by western spruce budworm. Canadian Journal of Forest Research. 13: 445-450.

Wykoff, W. R. 1986. Supplement to the user's guide for the Stand Prognosis Model—version 5.0. Gen. Tech. Rep. INT-208. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 36 p.

Wykoff, W. R.; Crookston, N. L.; Stage, A. R. 1982. User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

Ferguson, Dennis E. 1988. Growth of regeneration defoliated by spruce budworm in Idaho. Res. Pap. INT-393. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 13 p.

Mathematical equations are presented for predicting growth and development of regeneration as a function of species, tree condition, site characteristics, and western spruce budworm defoliation. The dataset consists of 1,183 host trees on which growth and defoliation were followed concurrently for 5 years. Probability of dieback is positively related to defoliation and negatively related to crown ratio. Height growth is negatively related to budworm defoliation and positively related to crown ratio. Crown ratio decreases with increasing defoliation, but the effect is delayed. Indications are that the probability of mortality is positively related to defoliation and negatively related to crown ratio.

KEYWORDS: *Choristoneura occidentalis*, reproduction, modeling, succession, forest management, planning

---

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

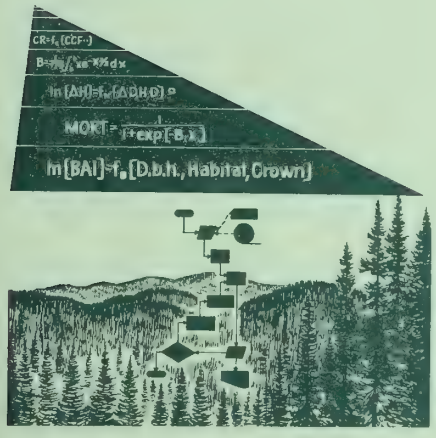
Research Paper
INT-394

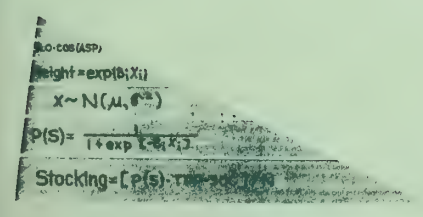
November 1988

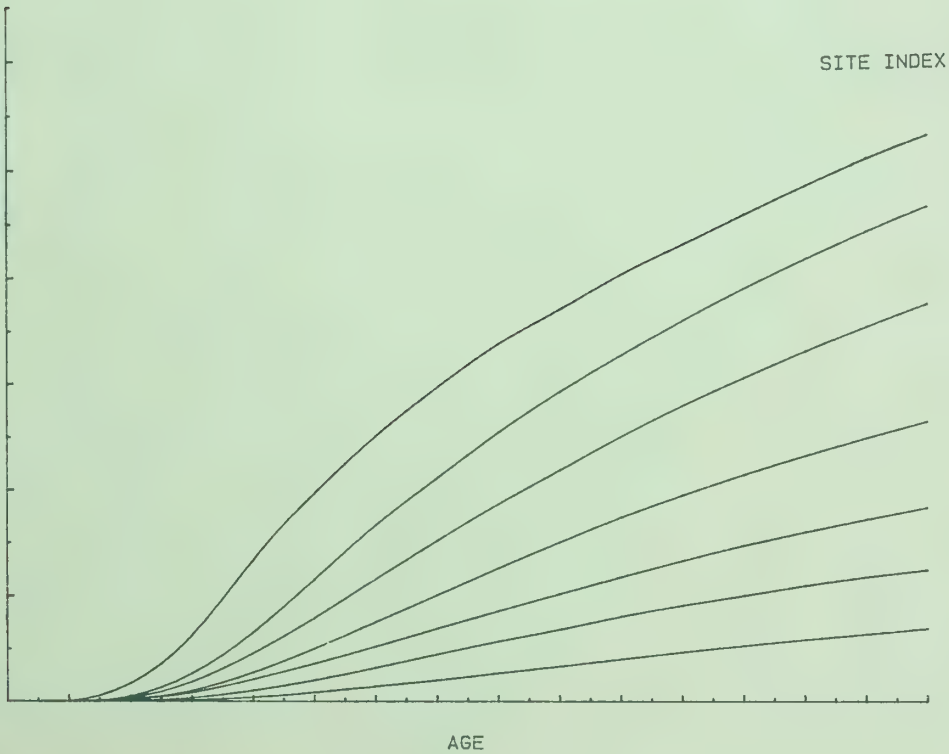
Selected Yield Tables for Plantations and Natural Stands in Inland Northwest Forests

Albert R. Stage
David L. Renner
Roger C. Chapman

PUBLIC DOCS







THE AUTHORS

ALBERT R. STAGE is principal mensurationist with the Forestry Sciences Laboratory, Intermountain Research Station, Moscow, ID.

DAVID L. RENNER is a forester with the Forestry Sciences Laboratory at Moscow, ID.

ROGER C. CHAPMAN is an associate professor of forest management, Department of Forestry and Range Management, Washington State University, Pullman.

ACKNOWLEDGMENTS

Tabulation of yields by site index and age was requested by members of the Inland Northwest Growth and Yield Cooperative, who also specified the species and management regimes to be represented.

RESEARCH SUMMARY

Yields arrayed by site index and age have been tabulated for plantations of 500 trees per acre, with five thinning regimes, for each of three planted species: Douglas-fir, grand fir, and western larch. In addition, yields have been tabulated for naturally regenerated stands of the grand fir-cedar-hemlock ecosystem of the Inland Empire. The yields were estimated with the Prognosis Model for Stand Development, version 5.2, including the Regeneration Establishment Model. Each planted species and the natural regeneration were simulated for the full range of site, geographic, and ecologic variables represented in a random inventory of the National Forests of the Inland Empire. Site index was obtained from the simulations by extracting heights of the 20 tallest trees per acre when they accumulated 50 rings at 4.5 feet.

Individual simulations were sorted into 10-foot site index classes and average yields were calculated. Weights in the averaging were proportional to the relative frequency with which the sites occur in the forests of the Inland Empire.

Simulations showed great variation in yields for stands of the same site index. Furthermore, comparisons between these yield tables for natural stands and 102 permanent sample plots show that these tables give less accurate estimates of growth than the Prognosis Model from which they were derived. Therefore, these yield tables should be used only when use of the Prognosis Model is precluded by lack of data on the site, geographic, and ecologic factors.

CONTENTS

Page

Introduction 1
Applicability 1
Methods 2
Definition of Variables 2
Yield Tables for Natural Regeneration 2
Yield Tables for Plantations 8
  Douglas-fir 8
  Grand fir 25
  Western larch 41
Comparison to Related Yield Estimates 55
References 56
Appendix Tables: Inventory Classes Used for Simulation
  Douglas-fir 57
  Grand fir 57
  Western larch 58
  Naturally regenerated stands 58

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Selected Yield Tables for Plantations and Natural Stands in Inland Northwest Forests

Albert R. Stage
David L. Renner
Roger C. Chapman

INTRODUCTION

This report contains yield tables arrayed by site index and age for average ecological and topographic situations in the Inland Empire. Yields were estimated by the Prognosis Model for Stand Development, version 5.2. Estimates are provided for plantations of Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and grand fir (*Abies grandis*) and for natural stands in the grand fir-cedar-hemlock ecosystem. Five thinning regimes are presented for the plantations.

Yield tables that represent estimates of volumes contained in forest stands have traditionally been presented with site index and stand age as the table stubs, and various attributes of the expected stand—merchantable volumes, total volumes, basal area, and mean diameter at breast height (d.b.h.)—in the body of the table.

Site index is only one factor influencing future yields. However, incorporating other productivity factors into the format of conventional yield tables, along with a multiplicity of alternative management regimes, would require extremely voluminous sets of tables. The obvious solution is to prepare the tables to specifications of the user with the Prognosis Model (Wykoff and others 1982).

Some information needs are not met by such yield-simulation procedures. In the most serious situation, the existing inventory may have been designed to provide only the traditional site index and age classification of the forest, precluding the use of the more definitive techniques.

Another information need—comparing yields between forest types or regions—is hampered if the forests being compared are not described by the same variables. Although site index and age definitions often vary from region to region and type to type, the problem is even more serious when the additional site variables are not used at all.

For these reasons, users or potential users of the Prognosis Model have asked to have yield information implicit in the Prognosis Model presented in the traditional format of site index and age. The tables in this publication are intended to meet that request.

APPLICABILITY

The tables presented here represent the forests of the Inland Empire, which includes northern Idaho, northeastern Washington, and western Montana.

Within the Inland Empire, the tables for natural stands represent the following habitat types:

Grand fir/pachistima
Cedar/pachistima
Hemlock/pachistima
Subalpine fir/pachistima

Yield estimates for Douglas-fir plantations represent, in addition to those for the naturally established stands, the following habitats:

Douglas-fir/ninebark
Douglas-fir/snowberry
Douglas-fir/pinegrass
Subalpine fir/menziesia
Subalpine fir/woodrush
Subalpine fir/twinflower
Mountain hemlock/menziesia

Yield estimates for western larch plantations represent, in addition to those for the naturally established stands, the following habitats:

Douglas-fir/ninebark
Spruce/pachistima
Grand fir/beargrass
Subalpine fir/devil's club
Subalpine fir/beargrass
Subalpine fir/twinflower
Subalpine fir/whortleberry
Mountain hemlock/beargrass
Mountain hemlock/menziesia

Yield estimates for grand fir plantations represent, in addition to those for the naturally established stands, the following habitats:

Grand fir/beargrass
Subalpine fir/menziesia
Subalpine fir/beargrass
Mountain hemlock/beargrass

Five management regimes are represented for plantations of each of the three species. Planting density and initial survival are assumed to provide 500 trees per acre 5 years after planting. In parentheses after each regime is a mnemonic code used to identify the regime on those figures that compare several regimes.

1. No thinning (000).
2. Precommercial thinning from below at 20 years to 250 trees per acre (P00).

3. Same as 2 with commercial thinning at 50 years to 100 trees per acre, such that the average d.b.h. before thinning is the same as after thinning (PC1).

4. Same as 3 but with commercial thinning from above at 50 years to 100 trees per acre (PCA).

5. Same as 3 but with commercial thinning from below at 50 years to 100 trees per acre (PCB).

Yields for natural stands are based on the clearcutting method of regeneration, with site preparation consisting of 64 percent of area burned and an additional 11 percent mechanically disturbed. No thinnings are scheduled.

METHODS

Growth and yield projections for 150 years were made using version 5.2 of the Stand Prognosis Model.

Geographic, topographic, and ecologic data to be used in the simulations were obtained from inventory plots that were a random sample of the forest. These plots represent the range and joint occurrence of site variables throughout the Inland Empire. The inventory plots were used to define the distribution of five major site variables influencing tree growth: geographic location (defined by National Forest), habitat type (Daubenmire and Daubenmire 1968), slope percentage, aspect (degrees from north), and elevation (hundreds of feet).

Combinations of these five variables constituted a "cell," each cell corresponding to a unique set of model coefficients in the Prognosis Model. The values used for the slope and elevation variables were the mean ±1 standard deviation within the geographic and habitat type classes. Aspect variation is represented by two classes corresponding to the maximum and minimum of the aspect effect on increment for that species. The appendix contains detailed information on the combinations of these variables and the nominal values used for the three planted species and naturally regenerated stands.

Initial stand conditions were defined by the Regeneration Establishment Model (Ferguson and others 1986) component of the Prognosis Model.

Site index was calculated for each projection by monitoring the simulated height growth for each tree record. Height at 50 years (rings at 4.5 feet) was calculated for each tree, then site index calculated as the average of the 20 trees per acre having the greater 50-year heights.

However, to prevent management treatment from influencing site calculations, each cell was assigned the site index value derived for the planting-no thinning management regime for that species.

Yields from the simulation were then sorted by 10-foot site index classes and management treatment and a weighted average yield value was calculated. Weights for each cell were proportional to the frequency with which inventory locations fell within the cell.

Although the site variables define a wide range of site productivity, there is still substantial variability within a cell. To represent this variability, multipliers of basal area increment for trees larger than 3 inches d.b.h., and height increment for smaller trees (<3 inches d.b.h.), were assigned to each cell. The multipliers were entered with the BAIMULT and REGHMULT keywords (Wykoff and others 1982). Logarithm of BAIMULT was selected randomly from a normal distribution having a mean of zero and standard deviation of 0.3. The choice of standard deviation was based on estimates of residual variation in growth histories of 102 permanent sample plots in northern Idaho (Stage 1987).

DEFINITIONS OF VARIABLES

Site index. Average height in feet of the tallest 20 trees per acre when the trees have 50 rings at 4.5 feet above ground level.

Age. Number of years from planting or from date of harvest or site preparation for natural-stand yields.

Top Height. Average height in feet of the 40 largest diameter (d.b.h.) trees per acre.

Volumes. Reported for three categories of size limits:

Total cubic feet includes all stems, from 1-foot stump to tip of main stem.

Merchantable cubic feet includes all stems greater than 7.0 inches d.b.h. from 1-foot stump to a top diameter inside bark of 4.5 inches.

Board feet Scribner (Kemp 1956) includes all stems greater than 7.0 inches d.b.h. from 1-foot stump to a top diameter inside bark of 4.5 inches.

Accretion (ACC in yield table headings). Periodic mean annual change in total cubic foot volume of trees surviving through the period,the length of which is indicated by column headed PRD yrs.

Mortality (MOR in yield table headings). Total cubic foot volume per year of trees dying in the period.

Total Yield. Standing volume plus volume removed by thinning, if any.

YIELD TABLES FOR NATURAL REGENERATION

Table 1 and figures 1, 2, and 3 represent the yields for the mix of species typically found in naturally regenerated stands of the grand fir-cedar-hemlock ecosystem. Grand fir is the most prevalent species followed by Douglas-fir and western white pine (*Pinus monticola*).

Entries for ages 5 and 10 represent only the established regeneration that would have been inventoried at age 5 years. From age 15 years on, the trees are those that would have been inventoried at age 15. Any subsequent regeneration is ignored.

Trends of tree d.b.h. with age and site index are displayed in figure 4.

The distribution of site indices represented in these simulated yields (fig. 5) was determined by the distribution of site variables in the inventory and by the range of the random variation of the growth multipliers.

Individual simulations showed surprising range in yield for the same site index. These variations are attributed to factors influencing initial stocking and time to reach 4.5 feet height. Figure 6, for example, shows a range in yield of approximately 10,000 cubic feet for site index class 60 at 120 years. This variation is nearly as large as the range of variation of the mean yields over the full range of sites represented in the yield tables.

Table 1—Yields of naturally regenerated stands in the grand fir-cedar-hemlock ecosystem

Site index	Age	Summary statistics														
			Volume per acre			Removals per acre							Growth			
		Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	D
			Ft^3	Ft^3	Bd ft		Ft^3	Ft^3	Bd ft	Ft^2		Ft	Yr	Ft^3	Ft^3	
40	5	681	0	0	0	0	0	0	0	1	2	1	5	0	0	0.5
	10	666	2	0	0	0	0	0	0	1	2	4	5	1	0	0.5
	20	1427	12	0	0	0	0	0	0	3	7	8	10	3	0	0.6
	30	1232	38	0	0	0	0	0	0	6	13	14	10	9	0	0.9
	40	1072	116	0	0	0	0	0	0	14	28	21	10	16	1	1.6
	50	952	269	0	0	0	0	0	0	29	50	28	10	21	2	2.4
	60	851	465	6	16	0	0	0	0	43	69	32	10	26	4	3.1
	70	753	690	14	45	0	0	0	0	57	85	37	10	29	6	3.7
	80	663	921	76	236	0	0	0	0	68	97	42	10	32	8	4.3
	90	582	1163	327	1029	0	0	0	0	78	106	47	10	33	10	5.0
	100	514	1403	544	1801	0	0	0	0	87	113	52	10	33	12	5.6
	110	456	1613	748	2576	0	0	0	0	93	118	56	10	37	14	6.1
	120	406	1847	1075	3778	0	0	0	0	99	122	60	10	37	15	6.7
	130	366	2063	1413	5074	0	0	0	0	104	126	64	10	33	17	7.2
	140	330	2217	1630	6006	0	0	0	0	106	125	67	10	40	20	7.7
	150	297	2410	1917	7254	0	0	0	0	109	125	71	0	0	0	8.2
50	5	716	0	0	0	0	0	0	0	1	2	2	5	1	0	0.4
	10	687	4	0	0	0	0	0	0	1	3	6	5	1	0	0.5
	20	1125	32	0	0	0	0	0	0	5	12	14	10	10	0	0.9
	30	955	133	0	0	0	0	0	0	15	28	23	10	25	1	1.7
	40	820	370	4	13	0	0	0	0	34	55	31	10	37	2	2.8
	50	731	724	92	286	0	0	0	0	57	83	38	10	47	4	3.8
	60	645	1147	413	1331	0	0	0	0	77	107	44	10	58	8	4.7
	70	559	1649	926	3224	0	0	0	0	99	127	51	10	59	11	5.7
	80	486	2127	1460	5308	0	0	0	0	115	143	57	10	68	16	6.6
	90	424	2650	2053	7829	0	0	0	0	131	156	63	10	71	20	7.5
	100	372	3153	2645	10491	0	0	0	0	143	164	69	10	65	25	8.4
	110	328	3562	3119	12872	0	0	0	0	150	168	75	10	76	30	9.2
	120	289	4021	3629	15654	0	0	0	0	158	171	81	10	68	31	10.0
	130	258	4394	4040	18039	0	0	0	0	163	172	86	10	68	35	10.8
	140	230	4718	4397	20205	0	0	0	0	165	170	90	10	66	38	11.5
	150	206	4998	4707	22183	0	0	0	0	167	167	95	0	0	0	12.2
60	5	707	0	0	0	0	0	0	0	1	2	2	5	1	0	0.4
	10	677	4	0	0	0	0	0	0	1	4	7	5	2	0	0.6
	20	1262	43	0	0	0	0	0	0	7	16	15	10	14	0	1.0
	30	1061	186	1	3	0	0	0	0	21	38	27	10	34	1	1.9
	40	908	520	62	191	0	0	0	0	46	72	35	10	49	3	3.0
	50	801	976	324	1084	0	0	0	0	71	103	44	10	61	7	4.0
	60	682	1510	815	2900	0	0	0	0	94	127	52	10	70	12	5.0
	70	578	2090	1437	5361	0	0	0	0	114	147	59	10	76	18	6.0
	80	492	2673	2088	8152	0	0	0	0	131	161	66	10	81	24	7.0
	90	420	3241	2727	11157	0	0	0	0	145	169	71	10	87	30	7.9
	100	360	3809	3353	14313	0	0	0	0	155	174	77	10	88	35	8.9
	110	311	4340	3927	17462	0	0	0	0	164	176	82	10	91	40	9.8
	120	271	4853	4483	20773	0	0	0	0	170	177	87	10	92	43	10.7
	130	238	5339	5004	23906	0	0	0	0	176	177	91	10	95	48	11.6
	140	210	5815	5504	27005	0	0	0	0	180	176	96	10	91	50	12.5
	150	186	6220	5928	29690	0	0	0	0	182	175	100	0	0	0	13.4
70	5	684	0	0	0	0	0	0	0	1	2	2	5	1	0	0.4
	10	656	6	0	0	0	0	0	0	2	4	8	5	5	0	0.7
	20	1197	99	1	3	0	0	0	0	14	26	20	10	33	0	1.4
	30	1028	423	63	206	0	0	0	0	38	61	33	10	67	2	2.6
	40	887	1068	440	1506	0	0	0	0	76	108	44	10	93	7	4.0
	50	774	1933	1212	4485	0	0	0	0	116	152	53	10	112	15	5.2
	60	656	2907	2225	8744	0	0	0	0	152	185	61	10	124	25	6.5
	70	553	3896	3267	13626	0	0	0	0	180	207	69	10	137	37	7.7
	80	467	4896	4340	19069	0	0	0	0	203	222	76	10	140	46	8.9
	90	396	5834	5334	24513	0	0	0	0	220	230	82	10	144	56	10.1
	100	338	6717	6269	29969	0	0	0	0	233	234	88	10	148	64	11.2
	110	291	7551	7141	35191	0	0	0	0	242	236	94	10	149	71	12.4
	120	252	8324	7944	40077	0	0	0	0	250	236	99	10	153	77	13.5
	130	221	9081	8724	44842	0	0	0	0	256	235	104	10	153	82	14.6
	140	194	9798	9460	49326	0	0	0	0	260	234	109	10	150	86	15.7
	150	172	10442	10118	53321	0	0	0	0	264	233	114	0	0	0	16.8

(con.)

Table 1 (Con.)

Site index	Age	Summary statistics														
			Volume per acre			Removals per acre							Growth			
		Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3	
80	5	758	0	0	0	0	0	0	0	1	2	2	5	1	0	0.4
	10	724	7	0	0	0	0	0	0	2	5	8	5	6	0	0.7
	20	1186	147	9	31	0	0	0	0	19	33	23	10	57	0	1.7
	30	1024	714	257	900	0	0	0	0	58	85	37	10	119	4	3.2
	40	877	1863	1210	4713	0	0	0	0	117	149	50	10	157	19	4.9
	50	728	3245	2588	10922	0	0	0	0	168	196	61	10	186	38	6.5
	60	585	4724	4117	18396	0	0	0	0	208	226	70	10	202	57	8.1
	70	474	6172	5605	26255	0	0	0	0	238	244	79	10	213	75	9.6
	80	387	7549	7043	34278	0	0	0	0	259	253	87	10	214	85	11.1
	90	321	8833	8367	41931	0	0	0	0	275	259	95	10	223	99	12.5
	100	268	10078	9641	49370	0	0	0	0	287	262	102	10	218	108	14.0
	110	228	11180	10770	55888	0	0	0	0	295	263	108	10	221	117	15.4
	120	196	12217	11834	61974	0	0	0	0	301	262	114	10	215	121	16.8
	130	170	13153	12789	67494	0	0	0	0	305	261	120	10	219	128	18.2
	140	148	14067	13718	72720	0	0	0	0	308	259	125	10	216	130	19.5
	150	131	14922	14586	77586	0	0	0	0	311	257	130	0	0	0	20.9
90	5	671	0	0	0	0	0	0	0	0	2	2	5	2	0	0.4
	10	641	8	0	0	0	0	0	0	2	5	9	5	8	0	0.8
	20	1147	191	16	54	0	0	0	0	22	38	26	10	78	0	1.9
	30	982	962	436	1576	0	0	0	0	69	96	42	10	160	4	3.6
	40	841	2516	1858	7400	0	0	0	0	142	172	55	10	210	21	5.6
	50	694	4403	3770	16259	0	0	0	0	206	229	68	10	239	50	7.4
	60	553	6290	5705	26282	0	0	0	0	252	260	77	10	268	78	9.1
	70	439	8186	7642	37038	0	0	0	0	287	278	86	10	284	105	11.0
	80	350	9972	9476	47607	0	0	0	0	312	287	94	10	283	125	12.8
	90	284	11553	11086	56899	0	0	0	0	328	291	103	10	294	145	14.5
	100	233	13039	12600	65629	0	0	0	0	339	291	110	10	290	158	16.3
	110	195	14362	13958	73343	0	0	0	0	347	290	116	10	277	162	18.1
	120	166	15514	15129	80020	0	0	0	0	351	288	121	10	283	171	19.7
	130	142	16643	16271	86341	0	0	0	0	354	286	127	10	284	180	21.4
	140	123	17687	17324	92138	0	0	0	0	357	283	132	10	265	170	23.1
	150	108	18635	18279	97315	0	0	0	0	359	281	137	0	0	0	24.7
100	5	759	0	0	0	0	0	0	0	1	2	2	5	2	0	0.5
	10	727	12	0	0	0	0	0	0	3	8	9	5	16	0	0.9
	20	1099	352	36	117	0	0	0	0	35	54	30	10	132	1	2.4
	30	936	1656	1054	3960	0	0	0	0	108	137	43	10	220	14	4.6
	40	776	3711	3058	12437	0	0	0	0	193	217	58	10	318	44	6.7
	50	624	6445	5776	26291	0	0	0	0	278	281	68	10	345	95	9.0
	60	486	8934	8306	40218	0	0	0	0	329	308	81	10	326	139	11.1
	70	380	10807	10258	51281	0	0	0	0	352	312	92	10	333	172	13.0
	80	298	12427	11937	61128	0	0	0	0	364	310	99	10	342	188	15.0
	90	238	13964	13514	70172	0	0	0	0	371	305	108	10	337	200	16.9
	100	195	15336	14913	78207	0	0	0	0	376	300	116	10	343	215	18.8
	110	160	16615	16217	85752	0	0	0	0	380	295	124	10	315	199	20.8
	120	137	17772	17386	92360	0	0	0	0	381	290	130	10	322	209	22.6
	130	117	18906	18531	98686	0	0	0	0	382	287	136	10	330	222	24.4
	140	101	19989	19623	104649	0	0	0	0	383	284	140	10	307	211	26.3
	150	89	20952	20592	109801	0	0	0	0	383	282	144	0	0	0	28.1

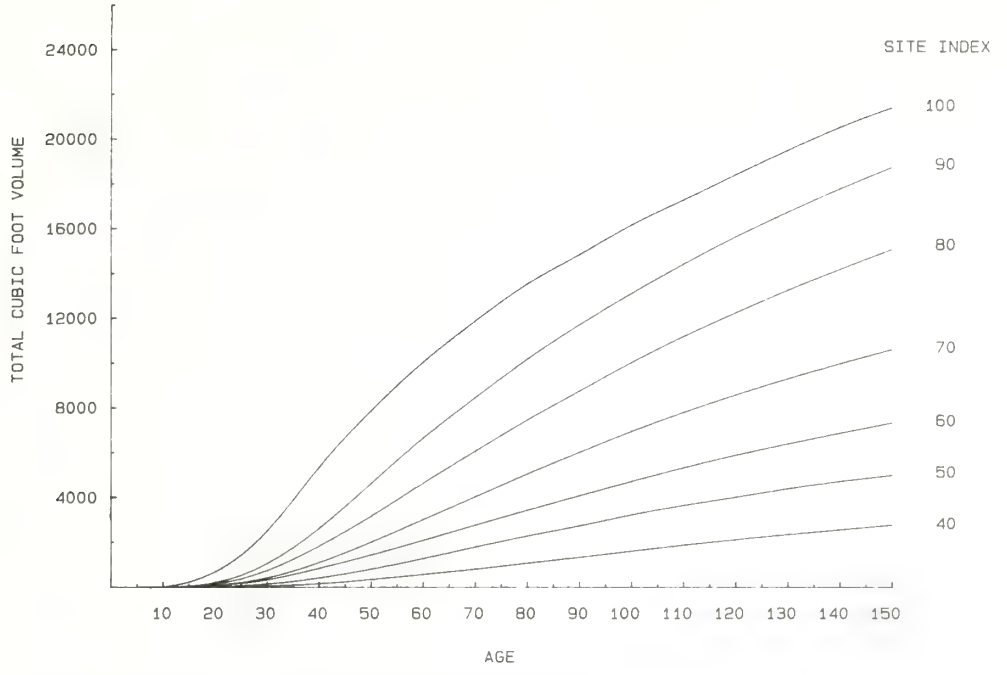


Figure 1—Natural regeneration yield curves for Inland Northwest forests of the grand fir-cedar-hemlock ecosystem (total cubic feet, all stems).

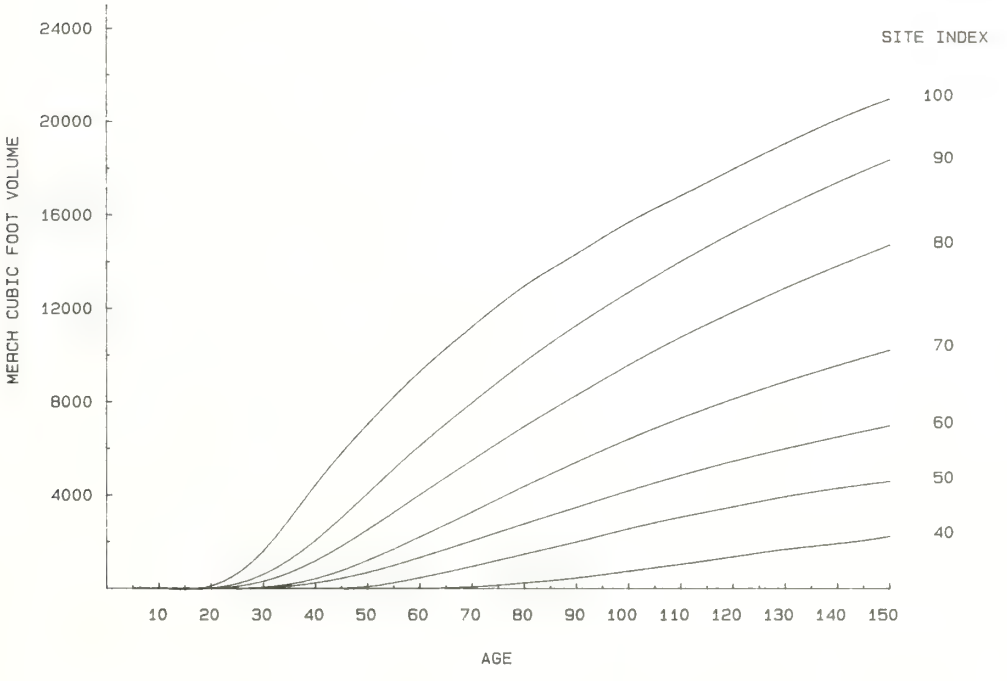


Figure 2—Natural regeneration yield curves for Inland Northwest forests of the grand fir-cedar-hemlock ecosystem (merchantable cubic feet, 4.5-inch top, stems greater than 7 inches d.b.h.).

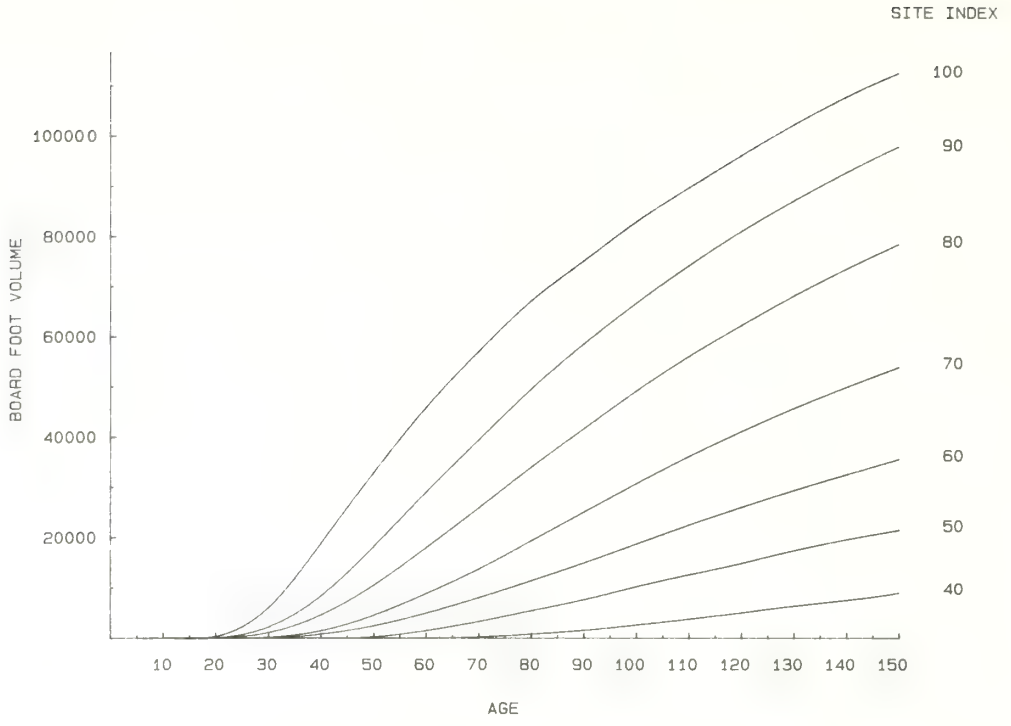


Figure 3—Natural regeneration yield curves for Inland Northwest forests of the grand fir-cedar-hemlock ecosystem (merchantable board feet [Scribner], 4.5-inch top, stems greater than 7 inches d.b.h.).

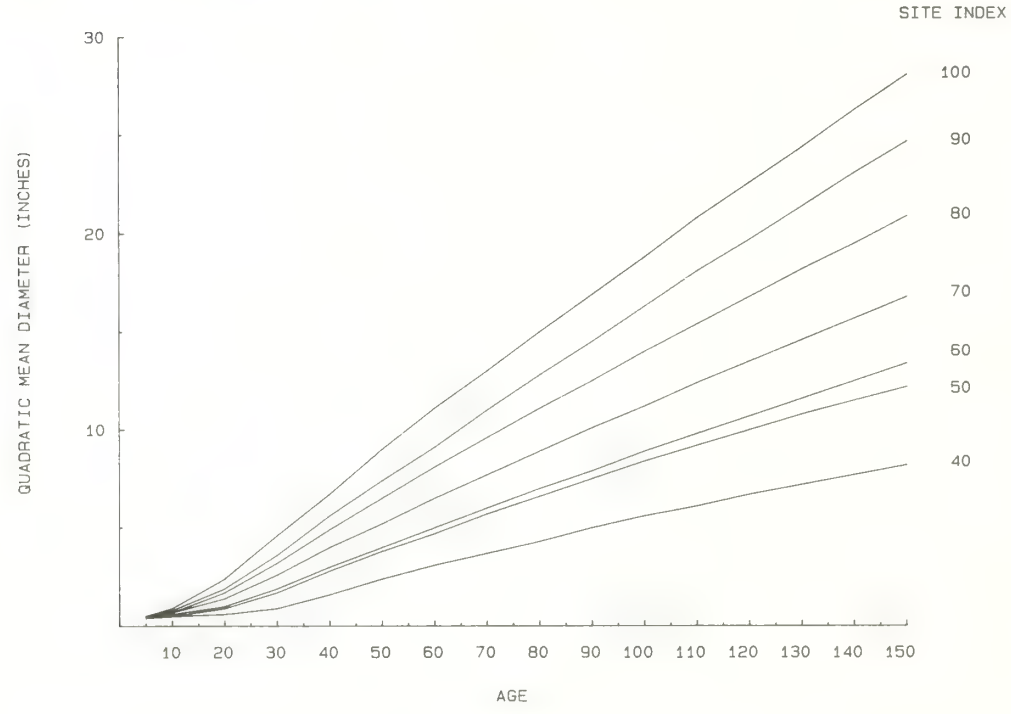


Figure 4—Quadratic mean diameter vs. age for natural regeneration in Inland Northwest forests.

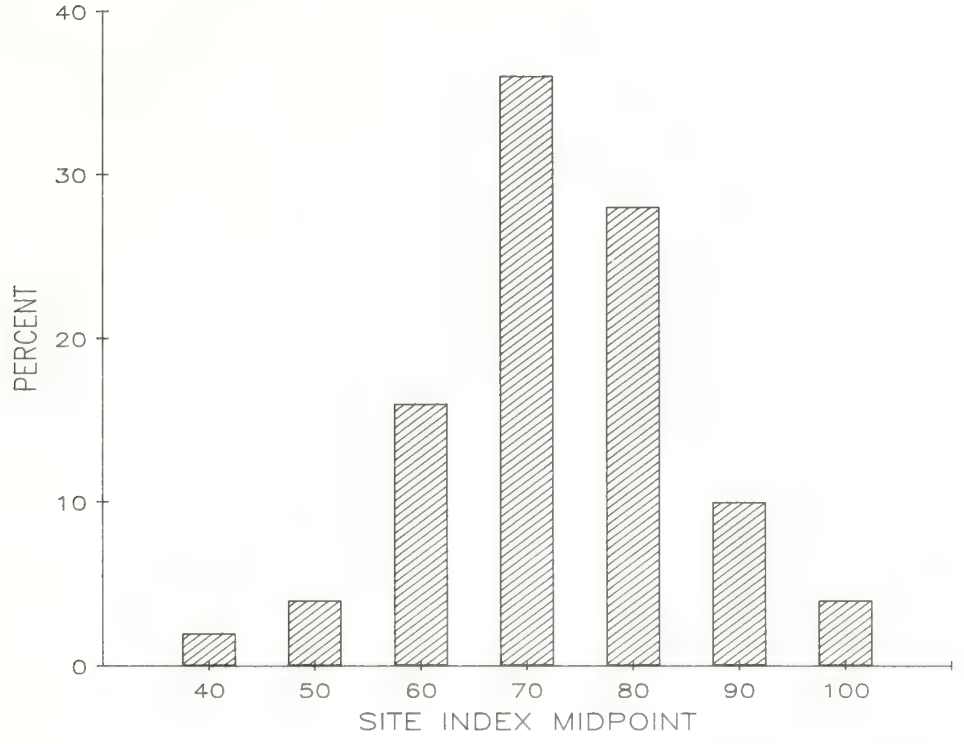


Figure 5—Distribution of natural regeneration site index values for Inland Northwest forests of the grand fir/cedar/hemlock ecosystem.

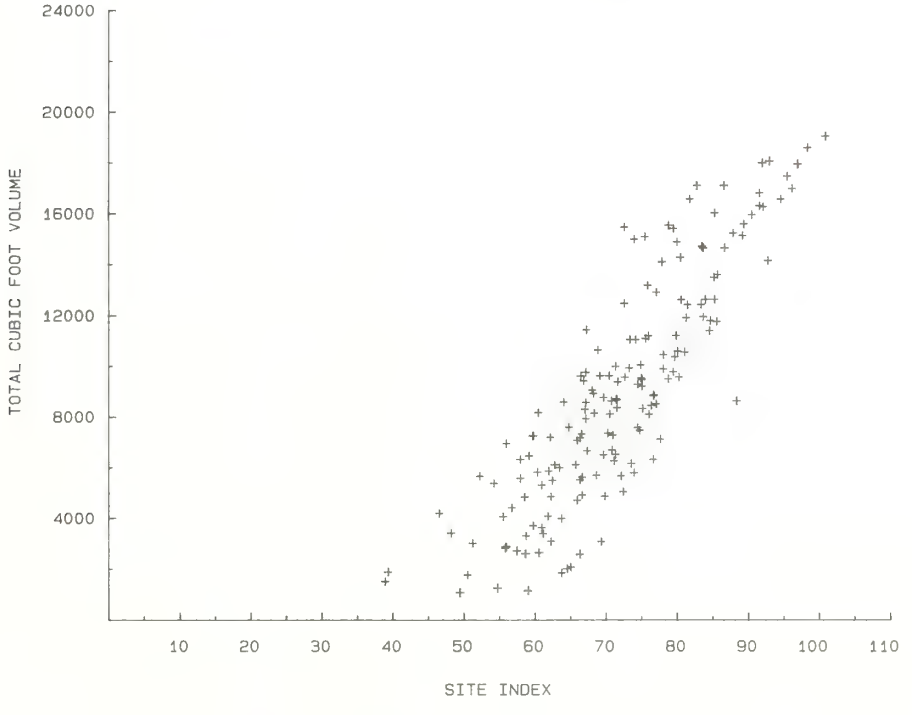


Figure 6—Natural regeneration yield vs. site index at 120 years of age (total cubic feet).

YIELD TABLES FOR PLANTATIONS

Yield estimates for plantations were produced assuming that there was **no** natural regeneration. On most sites in the Inland Empire, some natural regeneration can be expected. Therefore, the yields in these tables will apply only to stands in which early and repeated thinnings remove the natural regeneration. Simulation of the combined yields from planted as well as naturally regenerated trees would also be possible with the Prognosis Model.

Douglas-fir

Expected yields for plantations with 500 Douglas-fir trees per acre at 5 years are listed in tables 2 through 6 and figures 7 through 9 for the five management regimes. In comparison to the yields estimated for natural stands, Douglas-fir plantations are estimated to produce higher volumes at the early and middle ages because the height growth is faster at the early ages. This difference in height growth can be seen by comparing top heights at early ages for the same site index (table 2).

Variation of yields between simulations for the same site index is less than for the natural-stand yields because initial stocking is uniformly 500 trees per acre at 5 years (figs. 10, 11).

Treatment effects on mean d.b.h. are shown in figures 12 through 16. As expected, thinning from below produces the largest diameters, but response is slight on the lower site qualities.

Effects of thinning regimes on standing volume are compared in figures 17 through 22 for total cubic and merchantable board foot volumes. Effects of thinning regimes on total yield are compared in figures 23 through 28. Total yield was nearly constant for site index 90. For site indices 50 and 70, however, none of the thinning regimes matched the total yield of the unthinned plantations.

Table 2—Yields of Douglas-fir plantations having 500 trees per acre surviving 5 years, no thinning

Site index	Age	Summary statistics														
			Volume per acre			Removals per acre							Growth			
		Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3	
50	5	500	0		0	0	0	0	0	0	0	2	3	5	2	0.0
	10	473	10	0	0	0	0	0	0	1	5	8	10	4	0	0.7
	20	432	47	0	0	0	0	0	0	5	14	16	10	14	0	1.5
	30	391	186	0	0	0	0	0	0	18	34	25	10	30	0	2.9
	40	375	480	19	55	0	0	0	0	37	61	33	10	45	1	4.3
	50	359	913	251	767	0	0	0	0	61	88	41	10	54	4	5.6
	60	340	1413	755	2464	0	0	0	0	83	112	48	10	60	6	6.7
	70	321	1952	1370	4741	0	0	0	0	103	132	54	10	68	10	7.7
	80	300	2531	2051	7452	0	0	0	0	123	151	60	10	66	14	8.7
	90	281	3050	2648	10018	0	0	0	0	138	164	65	10	66	19	9.5
	100	262	3521	3172	12479	0	0	0	0	150	172	70	10	65	23	10.3
	110	242	3945	3650	14891	0	0	0	0	160	178	74	10	63	26	11.0
	120	224	4317	4053	17162	0	0	0	0	167	180	78	10	64	29	11.7
	130	207	4664	4419	19352	0	0	0	0	174	182	81	10	63	31	12.4
	140	192	4984	4751	21472	0	0	0	0	179	182	84	10	60	33	13.1
	150	177	5254	5032	23352	0	0	0	0	182	181	87	0	0	0	13.7
70	5	500	0	0	0	0	0	0	0	0	2	3	5	5	0	0.0
	10	478	27	0	0	0	0	0	0	4	10	12	10	20	0	1.2
	20	447	226	3	9	0	0	0	0	20	37	27	10	68	1	2.8
	30	416	898	218	705	0	0	0	0	61	90	40	10	107	3	5.2
	40	401	1939	1174	4041	0	0	0	0	110	144	50	10	126	11	7.1
	50	375	3090	2518	9263	0	0	0	0	153	186	60	10	134	24	8.7
	60	341	4187	3726	14645	0	0	0	0	187	215	67	10	139	38	10.0
	70	306	5192	4810	20115	0	0	0	0	212	231	75	10	136	50	11.3
	80	273	6052	5719	25276	0	0	0	0	229	238	81	10	130	60	12.4
	90	242	6759	6455	29831	0	0	0	0	240	240	86	10	130	68	13.5
	100	214	7378	7091	34084	0	0	0	0	248	237	91	10	126	73	14.6
	110	190	7914	7640	37871	0	0	0	0	253	234	96	10	122	76	15.6
	120	169	8374	8112	41226	0	0	0	0	255	228	101	10	116	79	16.7
	130	151	8748	8495	44068	0	0	0	0	256	222	105	10	110	80	17.7
	140	135	9053	8807	46422	0	0	0	0	256	216	108	10	109	81	18.6
	150	121	9340	9101	48605	0	0	0	0	255	210	112	0	0	0	19.6
90	5	500	0	0	0	0	0	0	0	0	2	4	5	16	0	0.0
	10	489	79	0	0	0	0	0	0	9	21	18	10	72	0	1.8
	20	472	801	253	771	0	0	0	0	54	83	40	10	171	3	4.6
	30	450	2484	1760	6211	0	0	0	0	131	169	56	10	200	18	7.3
	40	417	4306	3703	14366	0	0	0	0	197	232	69	10	200	44	9.3
	50	371	5863	5365	22468	0	0	0	0	241	265	78	10	211	73	10.9
	60	321	7239	6841	30564	0	0	0	0	271	281	85	10	209	94	12.5
	70	276	8385	8029	38071	0	0	0	0	291	284	93	10	187	101	13.9
	80	238	9246	8910	44064	0	0	0	0	301	281	98	10	188	112	15.2
	90	206	10005	9686	49320	0	0	0	0	307	275	102	10	182	115	16.5
	100	179	10675	10367	54156	0	0	0	0	312	268	107	10	181	121	17.8
	110	157	11275	10977	58378	0	0	0	0	314	262	112	10	174	120	19.2
	120	138	11820	11530	62202	0	0	0	0	316	255	116	10	166	118	20.5
	130	122	12299	12015	65560	0	0	0	0	317	249	119	10	158	118	21.8
	140	109	12697	12419	68274	0	0	0	0	317	243	123	10	147	114	23.1
	150	98	13028	12756	70585	0	0	0	0	316	237	126	0	0	0	24.3

Table 3—Yields of Douglas-fir plantations having 500 trees per acre surviving 5 years, precommercial thinning from below to 250 trees per acre at 20 years

Site index	Age	Summary statistics: Trees/ acre	Volume per acre: Total volume	Volume per acre: Merchant-able volume	Volume per acre: Merchant-able volume	Removals per acre: Trees/ acre	Removals per acre: Total volume	Removals per acre: Merchant-able volume	Removals per acre: Merchant-able volume	BA/ acre	CCF	Top height	Growth: PRD	Growth: ACC	Growth: MOR/ year	$\bar{D}$
			Ft^3	Ft^3	Bd ft		Ft^3	Ft^3	Bd ft	Ft^2		Ft	Yr	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	2	3	5	2	0	0.0
	10	473	10	0	0	0	0	0	0	1	5	8	10	4	0	0.7
	20	432	47	0	0	182	8	0	0	4	11	16	10	12	0	1.8
	30	232	155	0	0	0	0	0	0	14	26	25	10	24	0	3.3
	40	225	396	37	108	0	0	0	0	29	45	34	10	36	1	4.9
	50	217	741	260	829	0	0	0	0	46	64	43	10	42	2	6.2
	60	209	1143	704	2362	0	0	0	0	62	81	50	10	50	4	7.4
	70	200	1603	1254	4457	0	0	0	0	78	97	57	10	54	6	8.4
	80	191	2076	1804	6714	0	0	0	0	93	110	63	10	53	9	9.4
	90	181	2515	2286	8947	0	0	0	0	105	121	68	10	53	12	10.3
	100	171	2918	2714	11051	0	0	0	0	115	128	73	10	54	16	11.1
	110	161	3304	3113	13164	0	0	0	0	124	134	77	10	55	18	11.9
	120	151	3670	3495	15336	0	0	0	0	132	138	81	10	56	21	12.7
	130	141	4020	3850	17453	0	0	0	0	139	141	84	10	55	23	13.4
	140	132	4340	4172	19518	0	0	0	0	145	142	88	10	54	25	14.2
	150	124	4635	4469	21502	0	0	0	0	150	143	91	0	0	0	14.9
70	5	500	0	0	0	0	0	0	0	0	2	3	5	5	0	0.0
	10	478	27	0	0	0	0	0	0	4	10	12	10	20	0	1.2
	20	447	226	3	9	197	40	0	0	15	28	27	10	55	0	3.4
	30	242	732	224	721	0	0	0	0	47	66	40	10	87	2	5.9
	40	236	1589	1163	4042	0	0	0	0	83	105	52	10	108	6	8.0
	50	226	2601	2332	8828	0	0	0	0	118	138	62	10	117	15	9.8
	60	212	3622	3395	13877	0	0	0	0	148	163	70	10	123	25	11.3
	70	196	4599	4378	19136	0	0	0	0	173	180	78	10	122	35	12.7
	80	179	5462	5241	24234	0	0	0	0	191	189	84	10	118	43	14.0
	90	163	6212	5990	28926	0	0	0	0	205	194	90	10	117	50	15.2
	100	149	6878	6656	33273	0	0	0	0	216	196	95	10	114	57	16.3
	110	135	7449	7228	37105	0	0	0	0	223	196	100	10	111	62	17.4
	120	123	7943	7724	40470	0	0	0	0	228	195	104	10	104	64	18.5
	130	111	8339	8122	43225	0	0	0	0	231	192	108	10	105	69	19.5
	140	101	8695	8482	45688	0	0	0	0	233	189	112	10	98	69	20.5
	150	92	8984	8774	47718	0	0	0	0	233	185	116	0	0	0	21.5
90	5	500	0	0	0	0	0	0	0	0	2	4	5	16	0	0.0
	10	489	79	0	0	0	0	0	0	3	21	18	10	72	0	1.8
	20	472	801	253	771	222	135	0	0	42	61	40	10	137	1	5.6
	30	245	2026	1670	5960	0	0	0	0	99	122	57	10	171	3	8.6
	40	234	3649	3400	13473	0	0	0	0	152	172	71	10	183	25	10.9
	50	218	5229	4991	21796	0	0	0	0	195	204	82	10	184	46	12.8
	60	198	6615	6365	29808	0	0	0	0	227	222	89	10	176	62	14.5
	70	179	7756	7499	36916	0	0	0	0	249	230	94	10	172	74	15.9
	80	161	8738	8477	43399	0	0	0	0	265	234	100	10	173	87	17.3
	90	144	9598	9337	49138	0	0	0	0	276	235	105	10	152	87	18.7
	100	130	10255	9994	53601	0	0	0	0	283	233	109	10	158	97	20.0
	110	117	10865	10605	57717	0	0	0	0	288	231	114	10	153	97	21.2
	120	106	11427	11169	61368	0	0	0	0	292	228	118	10	155	104	22.5
	130	96	11939	11683	64679	0	0	0	0	295	225	122	10	152	104	23.7
	140	87	12413	12159	67653	0	0	0	0	297	222	125	10	138	103	25.0
	150	79	12765	12514	69883	0	0	0	0	298	218	129	0	0	0	26.3

Table 4—Yields of Douglas-fir plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning from below to 100 trees per acre at 50 years

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	2	3	5	2	0	0.0
	10	473	10	0	0	0	0	0	0	1	5	8	10	4	0	0.7
	20	432	47	0	0	182	8	0	0	4	11	16	10	12	0	1.8
	30	232	155	0	0	0	0	0	0	14	26	25	10	24	0	3.3
	40	225	396	37	108	0	0	0	0	29	45	34	10	36	1	4.9
	50	217	741	260	829	117	263	1	2	28	37	43	10	26	1	7.2
	60	98	730	598	2033	0	0	0	0	38	47	50	10	30	2	8.4
	70	95	1012	915	3335	0	0	0	0	47	56	57	10	32	3	9.5
	80	92	1302	1213	4653	0	0	0	0	56	64	63	10	35	4	10.5
	90	89	1607	1517	6128	0	0	0	0	64	71	68	10	36	6	11.5
	100	86	1914	1822	7726	0	0	0	0	72	77	73	10	36	7	12.4
	110	82	2200	2106	9296	0	0	0	0	79	82	77	10	36	9	13.3
	120	79	2469	2373	10846	0	0	0	0	85	85	81	10	37	11	14.1
	130	75	2732	2633	12434	0	0	0	0	91	88	84	10	37	12	14.9
	140	72	2983	2882	14010	0	0	0	0	96	90	88	10	37	13	15.7
	150	68	3222	3119	15565	0	0	0	0	101	92	91	0	0	0	16.5
70	5	500	0	0	0	0	0	0	0	0	2	3	5	5	0	0.0
	10	478	27	0	0	0	0	0	0	4	10	12	10	20	0	1.2
	20	447	226	3	9	197	40	0	0	15	28	27	10	55	0	3.4
	30	242	732	224	721	0	0	0	0	47	66	40	10	87	2	5.9
	40	236	1589	1163	4042	0	0	0	0	83	105	52	10	108	6	8.0
	50	226	2601	2332	8828	126	993	817	2792	71	79	62	10	77	5	11.4
	60	97	2326	2219	9623	0	0	0	0	92	96	70	10	82	10	13.2
	70	92	3053	2935	13659	0	0	0	0	111	108	78	10	84	14	14.8
	80	88	3756	3628	17845	0	0	0	0	128	117	84	10	90	20	16.3
	90	83	4453	4316	22134	0	0	0	0	142	125	90	10	90	25	17.7
	100	78	5105	4961	26157	0	0	0	0	155	131	96	10	87	30	19.1
	110	73	5677	5528	29731	0	0	0	0	165	135	101	10	88	35	20.3
	120	68	6209	6055	32999	0	0	0	0	173	138	105	10	83	36	21.5
	130	64	6680	6523	35889	0	0	0	0	180	140	109	10	78	41	22.6
	140	60	7052	6893	38160	0	0	0	0	184	141	113	10	80	45	23.7
	150	56	7396	7237	40252	0	0	0	0	187	141	116	0	0	0	24.7
90	5	500	0	0	0	0	0	0	0	0	2	4	5	16	0	0.0
	10	489	79	0	0	0	0	0	0	9	21	18	10	72	0	1.8
	20	472	801	253	771	222	135	0	0	42	61	40	10	137	1	5.6
	30	245	2026	1670	5960	0	0	0	0	99	122	57	10	171	9	8.6
	40	234	3649	3400	13473	0	0	0	0	152	172	71	10	183	25	10.9
	50	218	5229	4991	21796	118	1855	1745	6717	120	117	82	10	132	15	14.8
	60	96	4549	4403	22039	0	0	0	0	148	134	90	10	143	25	16.8
	70	90	5734	5571	29357	0	0	0	0	174	148	97	10	143	34	18.8
	80	85	6828	6653	35963	0	0	0	0	195	159	104	10	125	40	20.6
	90	79	7684	7500	41164	0	0	0	0	210	166	109	10	139	55	22.0
	100	74	8532	8340	46226	0	0	0	0	223	171	114	10	118	52	23.6
	110	69	9192	8995	50138	0	0	0	0	233	174	118	10	119	61	24.9
	120	64	9770	9569	53534	0	0	0	0	240	176	121	10	113	64	26.2
	130	60	10269	10066	56440	0	0	0	0	244	177	125	10	121	71	27.3
	140	56	10763	10559	59378	0	0	0	0	249	177	128	10	104	65	28.7
	150	52	11153	10948	61649	0	0	0	0	252	176	131	0	0	0	29.8

Table 5—Yields of Douglas-fir plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning from above to 100 trees per acre at 50 years

Site index	Age	Trees/ acre	Summary statistics: Volume per acre: Total volume	Volume per acre: Merchantable volume	Volume per acre: Merchantable volume	Removals per acre: Trees/ acre	Removals per acre: Total volume	Removals per acre: Merchantable volume	Removals per acre: Merchantable volume	BA/ acre	CCF	Top height	Growth: PRD	Growth: ACC	Growth: MOR/ year	$\bar{D}$
			Ft³	*Ft³*	*Bd ft*		*Ft³*	*Ft³*	*Bd ft*	*Ft²*		*Ft*	*Yr*	*Ft³*	*Ft³*	
50	5	500	0	0	0	0	0	0	0	0	2	3	5	2	0	0.0
	10	473	10	0	0	0	0	0	0	1	5	8	10	4	0	0.7
	20	432	47	0	0	182	8	0	0	4	11	16	10	12	0	1.8
	30	232	155	0	0	0	0	0	0	14	26	25	10	24	0	3.3
	40	225	396	37	108	0	0	0	0	29	45	34	10	36	1	4.9
	50	217	741	260	829	117	533	260	828	14	22	34	10	18	1	5.1
	60	95	376	114	351	0	0	0	0	21	29	43	10	25	1	6.4
	70	92	613	409	1374	0	0	0	0	30	38	52	10	30	2	7.7
	80	90	893	741	2670	0	0	0	0	39	47	60	10	31	2	8.9
	90	87	1180	1074	4079	0	0	0	0	47	55	67	10	32	4	10.0
	100	84	1462	1369	5458	0	0	0	0	54	61	72	10	33	5	10.9
	110	80	1738	1646	6868	0	0	0	0	61	67	77	10	36	7	11.8
	120	77	2032	1942	8491	0	0	0	0	69	71	82	10	34	8	12.8
	130	74	2298	2206	10021	0	0	0	0	75	75	85	10	36	10	13.6
	140	70	2561	2468	11624	0	0	0	0	80	78	89	10	36	11	14.5
	150	67	2814	2719	13210	0	0	0	0	85	81	93	0	0	0	15.3
70	5	500	0	0	0	0	0	0	0	0	2	3	5	5	0	0.0
	10	478	27	0	0	0	0	0	0	4	10	12	10	20	0	1.2
	20	447	226	3	0	197	40	0	0	15	28	27	10	55	0	3.4
	30	242	732	224	721	0	0	0	0	47	66	40	10	87	2	5.9
	40	236	1589	1163	4042	0	0	0	0	83	105	52	10	108	6	8.0
	50	226	2601	2332	8828	126	1869	1755	6894	35	44	53	10	54	4	8.0
	60	95	1233	1137	4262	0	0	0	0	51	60	64	10	69	4	9.9
	70	91	1878	1780	7321	0	0	0	0	69	76	74	10	78	7	11.8
	80	87	2591	2486	11119	0	0	0	0	88	89	82	10	82	11	13.6
	90	83	3304	3190	15294	0	0	0	0	105	100	89	10	87	15	15.2
	100	79	4023	3900	19632	0	0	0	0	120	109	96	10	83	19	16.7
	110	75	4660	4530	23525	0	0	0	0	133	115	101	10	84	26	18.0
	120	70	5242	5107	27123	0	0	0	0	143	120	106	10	82	29	19.3
	130	66	5774	5634	30399	0	0	0	0	152	124	111	10	82	33	20.5
	140	62	6261	6118	33358	0	0	0	0	159	126	115	10	78	35	21.7
	150	58	6691	6545	35980	0	0	0	0	165	128	119	0	0	0	22.8
90	5	500	0	0	0	0	0	0	0	0	2	4	5	16	0	0.0
	10	489	79	0	0	0	0	0	0	9	21	18	10	72	0	1.8
	20	472	801	253	771	222	135	0	0	42	61	40	10	137	1	5.6
	30	245	2026	1670	5960	0	0	0	0	99	122	57	10	171	9	8.6
	40	234	3649	3400	13473	0	0	0	0	152	172	71	10	183	25	10.9
	50	218	5229	4991	21796	118	3733	3588	16441	61	71	65	10	99	8	10.6
	60	94	2401	2296	9766	0	0	0	0	86	90	77	10	131	8	12.9
	70	91	3630	3506	16764	0	0	0	0	117	111	88	10	135	15	15.3
	80	87	4832	4690	24025	0	0	0	0	144	128	97	10	148	25	17.4
	90	82	6069	5911	31418	0	0	0	0	170	142	104	10	133	32	19.5
	100	78	7074	6904	37573	0	0	0	0	189	152	110	10	120	40	21.1
	110	73	7874	7696	42374	0	0	0	0	202	158	114	10	139	52	22.6
	120	68	8739	8553	47490	0	0	0	0	216	164	120	10	116	49	24.2
	130	64	9411	9221	51471	0	0	0	0	225	167	123	10	117	61	25.5
	140	59	9976	9781	54752	0	0	0	0	232	169	127	10	112	64	26.8
	150	55	10457	10262	57575	0	0	0	0	237	169	130	0	0	0	28.0

Table 6—Yields of Douglas-fir plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning to 100 trees per acre at 50 years such that the mean d.b.h. before and after thinning is the same

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	2	3	5	2	0	0.0
	10	473	10	0	0	0	0	0	0	1	5	8	10	4	0	0.7
	20	432	47	0	0	182	8	0	0	4	11	16	10	12	0	1.8
	30	232	155	0	0	0	0	0	0	14	26	25	10	24	0	3.3
	40	225	396	37	108	0	0	0	0	29	45	34	10	36	1	4.9
	50	217	741	260	829	117	400	140	448	21	30	41	10	22	1	6.2
	60	97	557	358	1203	0	0	0	0	30	38	49	10	28	1	7.5
	70	94	821	665	2379	0	0	0	0	38	47	56	10	31	2	8.7
	80	91	1107	984	3724	0	0	0	0	47	56	63	10	31	3	9.8
	90	88	1384	1277	5069	0	0	0	0	55	62	68	10	31	5	10.8
	100	84	1645	1549	6391	0	0	0	0	62	68	72	10	33	6	11.6
	110	80	1914	1822	7852	0	0	0	0	69	72	77	10	34	8	12.5
	120	77	2181	2089	9366	0	0	0	0	75	76	81	10	34	9	13.4
	130	73	2429	2335	10838	0	0	0	0	80	79	85	10	36	11	14.2
	140	70	2680	2584	12379	0	0	0	0	85	82	88	10	36	11	15.0
	150	66	2924	2828	13919	0	0	0	0	90	84	91	0	0	0	15.8
70	5	500	0	0	0	0	0	0	0	0	2	3	5	5	0	0.0
	10	478	27	0	0	0	0	0	0	4	10	12	10	20	0	1.2
	20	447	226	3	9	197	40	0	0	15	28	27	10	55	0	3.4
	30	242	732	224	721	0	0	0	0	47	66	40	10	87	2	5.9
	40	236	1589	1163	4042	0	0	0	0	83	105	52	10	108	6	8.0
	50	226	2601	2332	8828	126	1444	1294	4897	53	61	60	10	63	4	9.8
	60	96	1747	1646	6784	0	0	0	0	70	77	69	10	75	7	11.6
	70	92	2433	2326	10388	0	0	0	0	89	91	77	10	79	10	13.4
	80	87	3118	3003	14260	0	0	0	0	106	102	84	10	79	14	14.9
	90	83	3768	3645	18153	0	0	0	0	120	110	90	10	82	19	16.3
	100	78	4398	4267	21983	0	0	0	0	133	117	95	10	80	23	17.7
	110	74	4964	4828	25471	0	0	0	0	144	121	100	10	81	29	18.9
	120	69	5490	5350	28716	0	0	0	0	153	125	105	10	79	32	20.1
	130	65	5959	5815	31600	0	0	0	0	160	128	109	10	77	35	21.3
	140	60	6380	6234	34183	0	0	0	0	166	129	113	10	77	38	22.4
	150	56	6765	6617	36520	0	0	0	0	170	130	117	0	0	0	23.5
90	5	500	0	0	0	0	0	0	0	0	2	4	5	16	0	0.0
	10	489	79	0	0	0	0	0	0	9	21	18	10	72	0	1.8
	20	472	801	253	771	222	135	0	0	42	61	40	10	137	1	5.6
	30	245	2026	1670	5960	0	0	0	0	99	122	57	10	171	9	8.6
	40	234	3649	3400	13473	0	0	0	0	152	172	71	10	183	25	10.9
	50	218	5229	4991	21796	118	2816	2688	11723	90	94	77	10	113	10	12.8
	60	95	3444	3318	15780	0	0	0	0	116	112	86	10	123	15	15.0
	70	91	4530	4389	22187	0	0	0	0	142	127	93	10	123	22	16.9
	80	86	5540	5386	28284	0	0	0	0	163	140	100	10	132	32	18.6
	90	81	6541	6375	34388	0	0	0	0	182	149	106	10	118	37	20.3
	100	76	7348	7173	39220	0	0	0	0	197	156	111	10	126	47	21.8
	110	71	8145	7964	43986	0	0	0	0	209	161	115	10	125	51	23.3
	120	66	8887	8699	48393	0	0	0	0	220	165	120	10	125	58	24.7
	130	62	9554	9362	52290	0	0	0	0	229	168	124	10	121	62	26.1
	140	57	10150	9954	55795	0	0	0	0	236	170	127	10	111	64	27.5
	150	53	10617	10419	58533	0	0	0	0	241	170	130	0	0	0	28.7

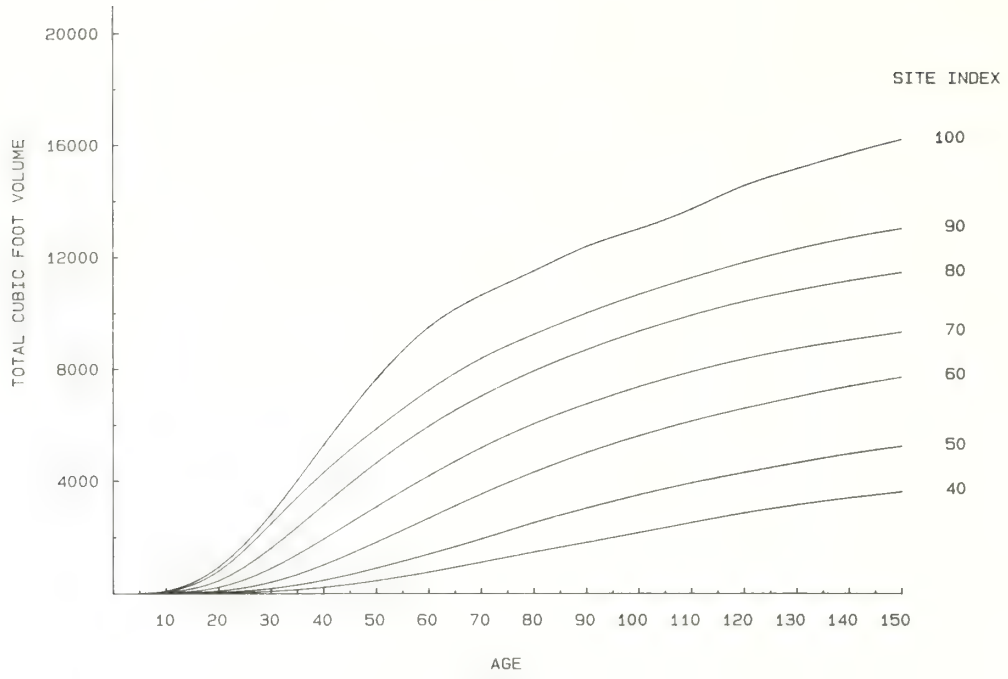


Figure 7—Douglas-fir yield curves for unthinned plantations in Inland Northwest forests (total cubic feet, all stems).

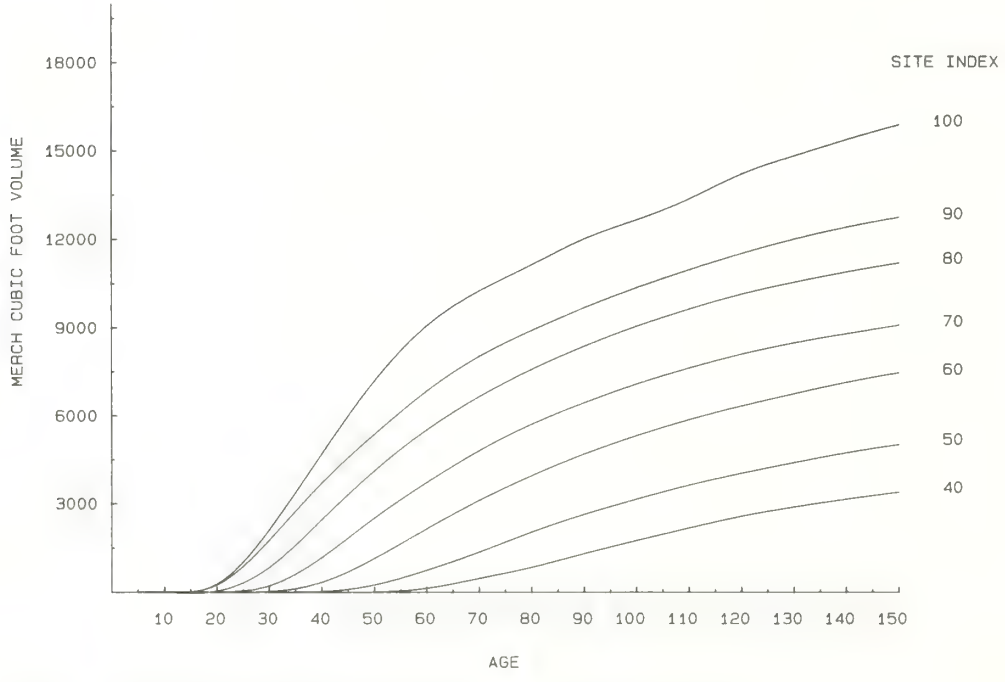


Figure 8—Douglas-fir yield curves for unthinned plantations in Inland Northwest forests (merchantable cubic feet, 4.5-inch top, stems greater than 7 inches d.b.h.).

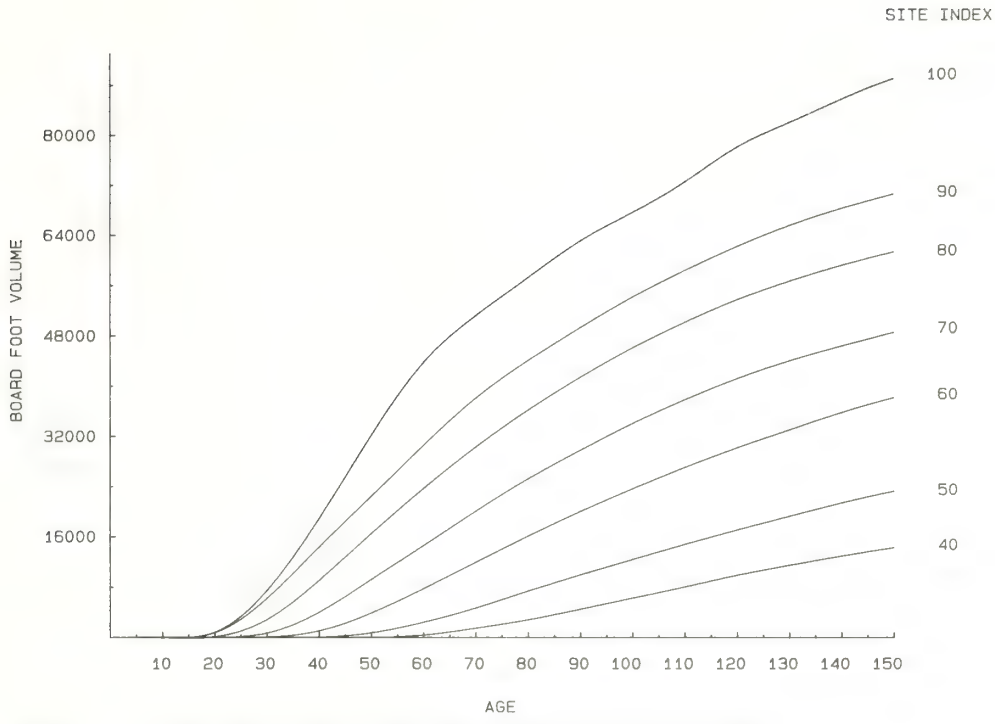


Figure 9—Douglas-fir yield curves for unthinned plantations in Inland Northwest forests (merchantable board feet [Scribner], 4.5-inch top, stems greater than 7 inches d.b.h.).

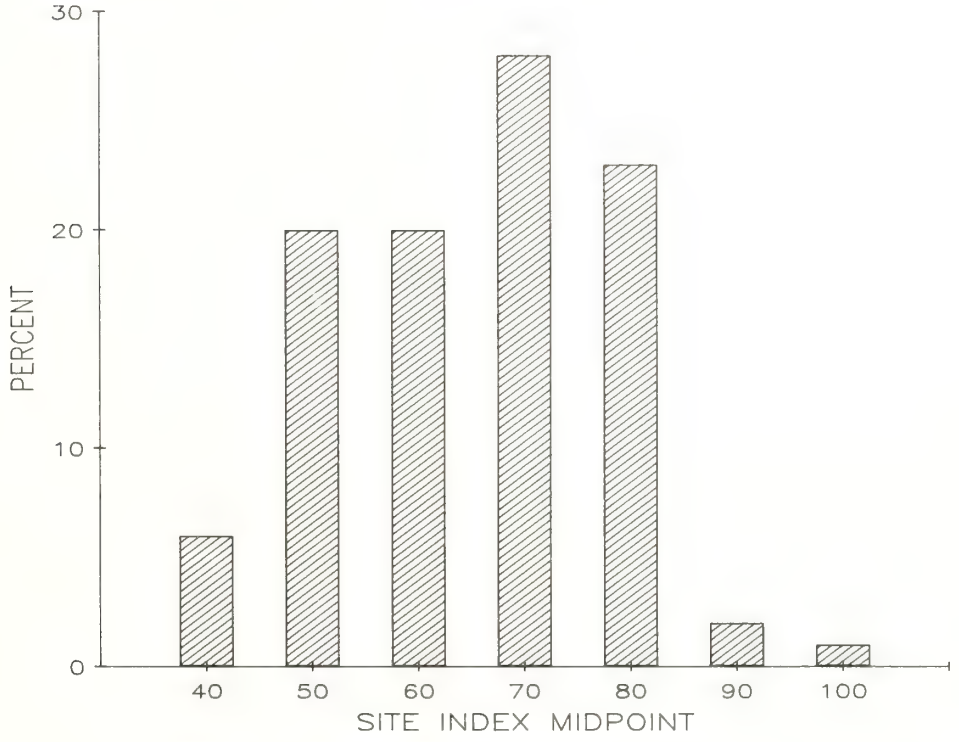


Figure 10—Distribution of Douglas-fir plantation site index values for Inland Northwest forests.

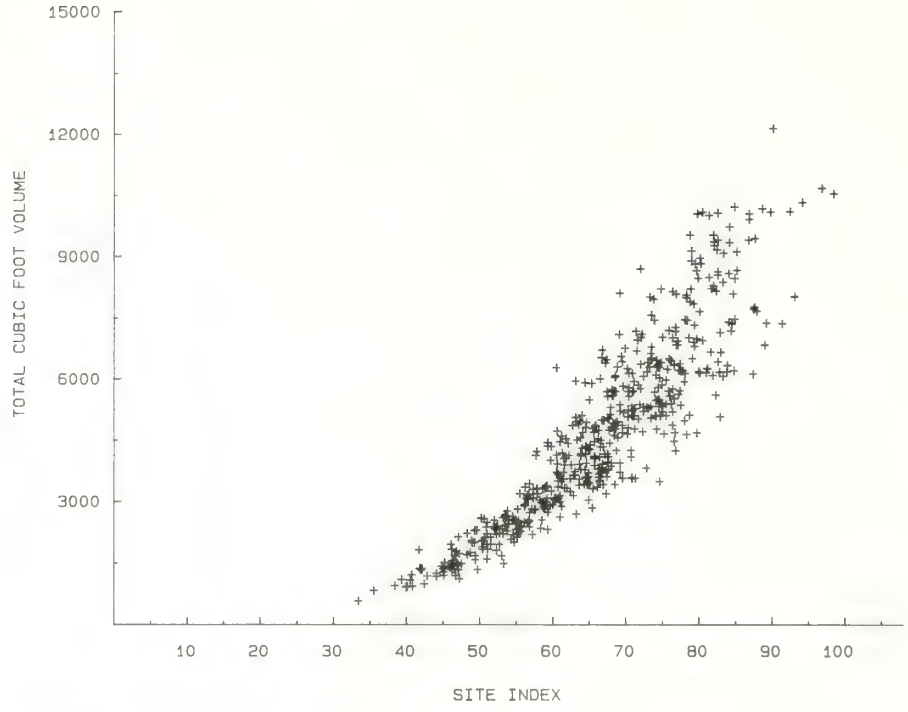


Figure 11—Douglas-fir yield vs. site index at 70 years of age (total cubic feet).

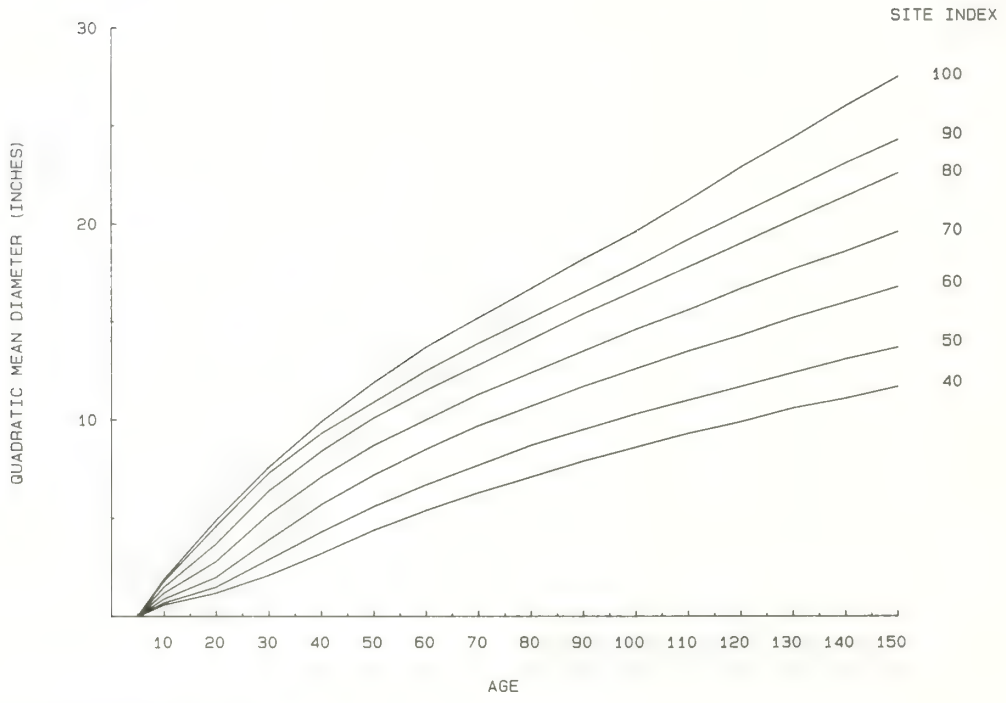


Figure 12—Quadratic mean diameter vs. age for Douglas-fir unthinned plantations in Inland Northwest forests.

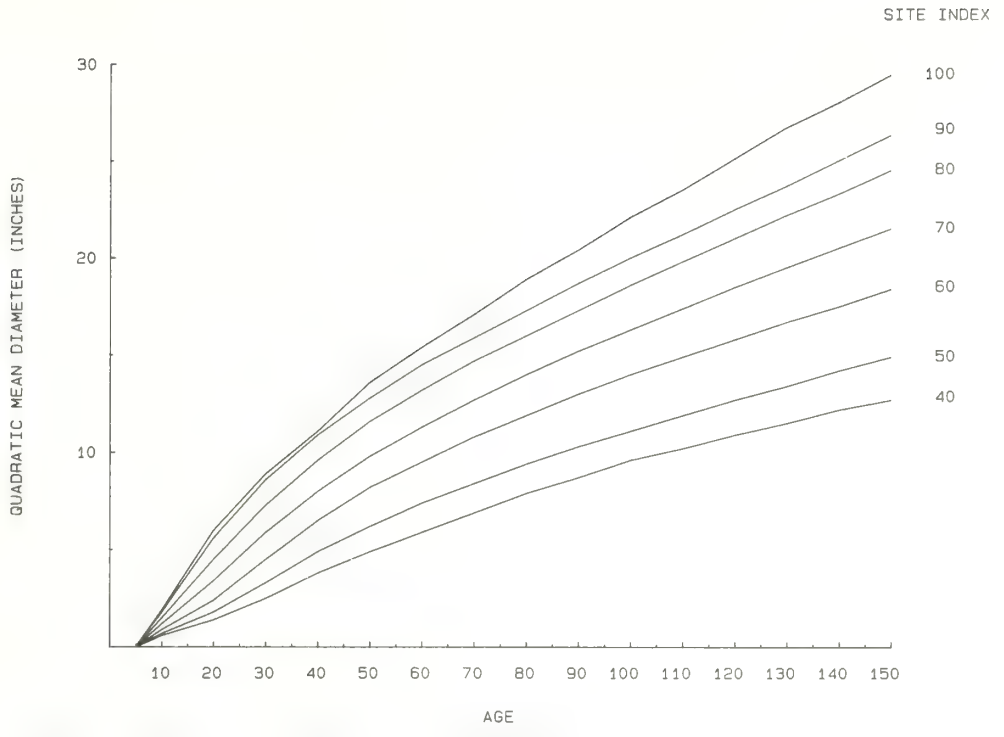


Figure 13—Quadratic mean diameter vs. age for Douglas-fir precommercial thinning to 250 trees per acre at 20 years in Inland Northwest forests.

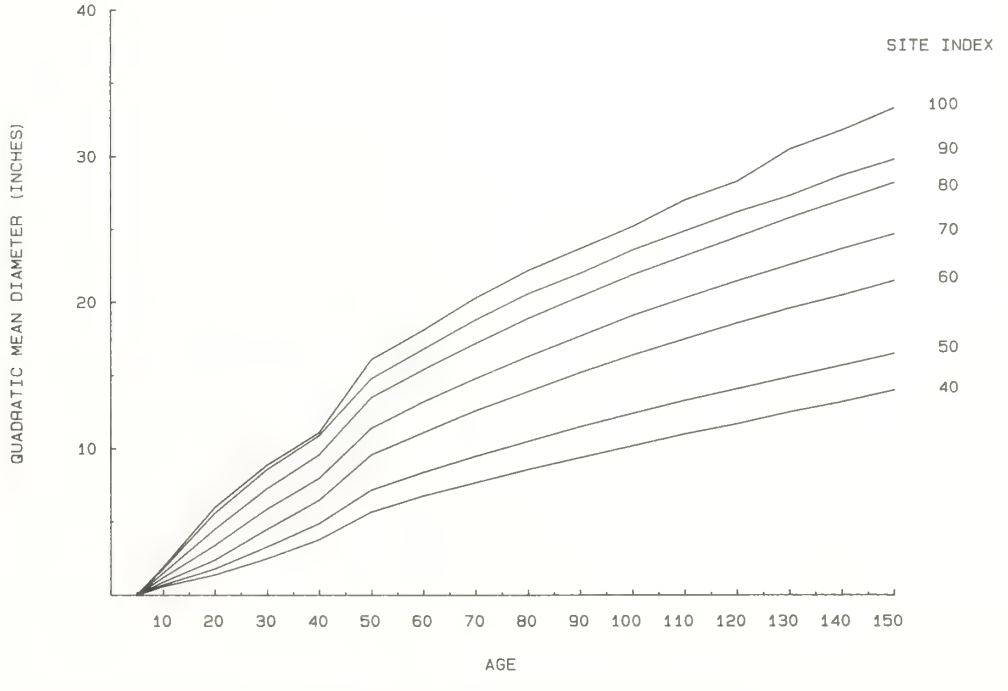


Figure 14—Quadratic mean diameter vs. age for Douglas-fir precommercial thinning to 250 trees per acre at 20 years and commercial thinning from below to 100 trees per acre at 50 years in Inland Northwest forests.

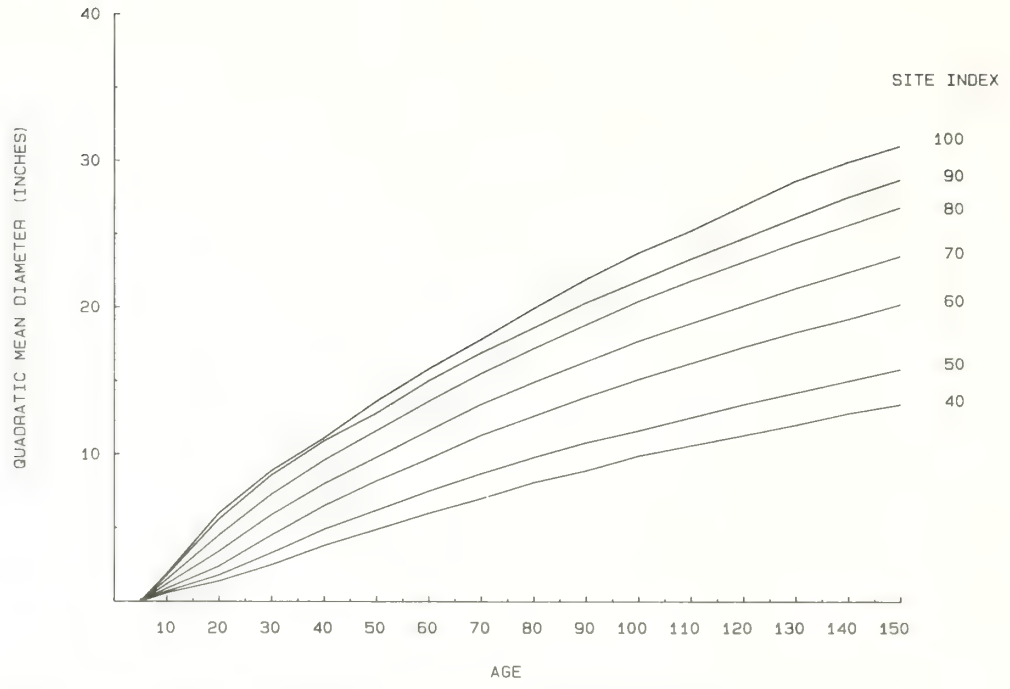


Figure 15—Quadratic mean diameter vs. age for Douglas-fir precommercial thinning to 250 trees per acre at 20 years and commercial thinning to 100 trees per acre at 50 years such that the mean d.b.h. before and after thinning is the same.

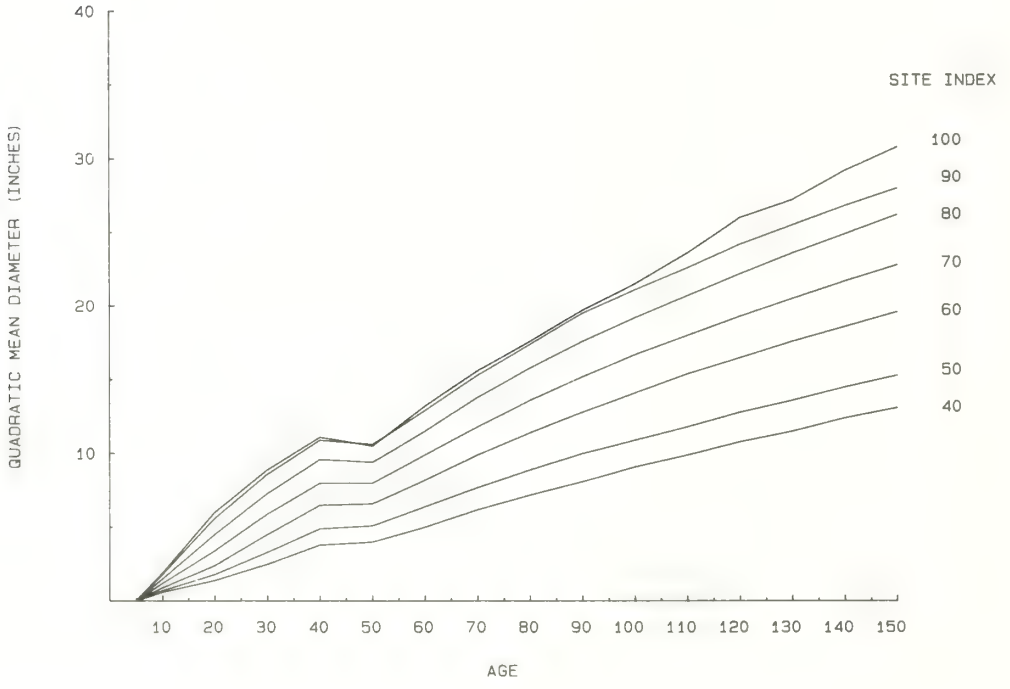


Figure 16—Quadratic mean diameter vs. age for Douglas-fir precommercial thinning to 250 trees per acre at 20 years and commercial thinning from above to 100 trees per acre at 50 years in Inland Northwest forests.

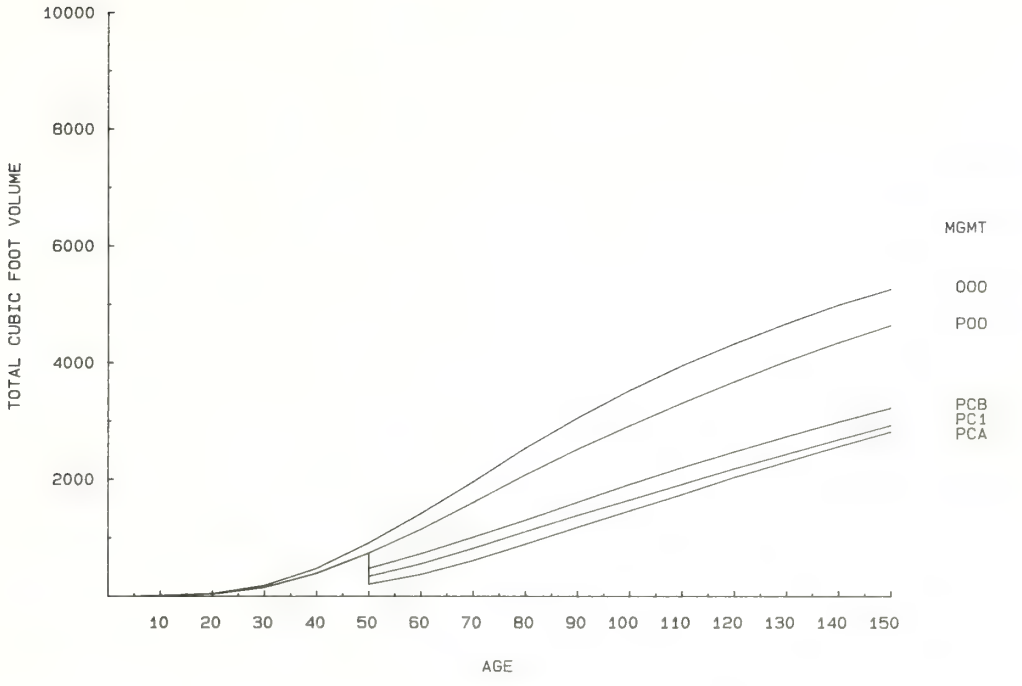


Figure 17—Effect of thinning on standing volume of Douglas-fir plantations (total cubic feet), site index 50.

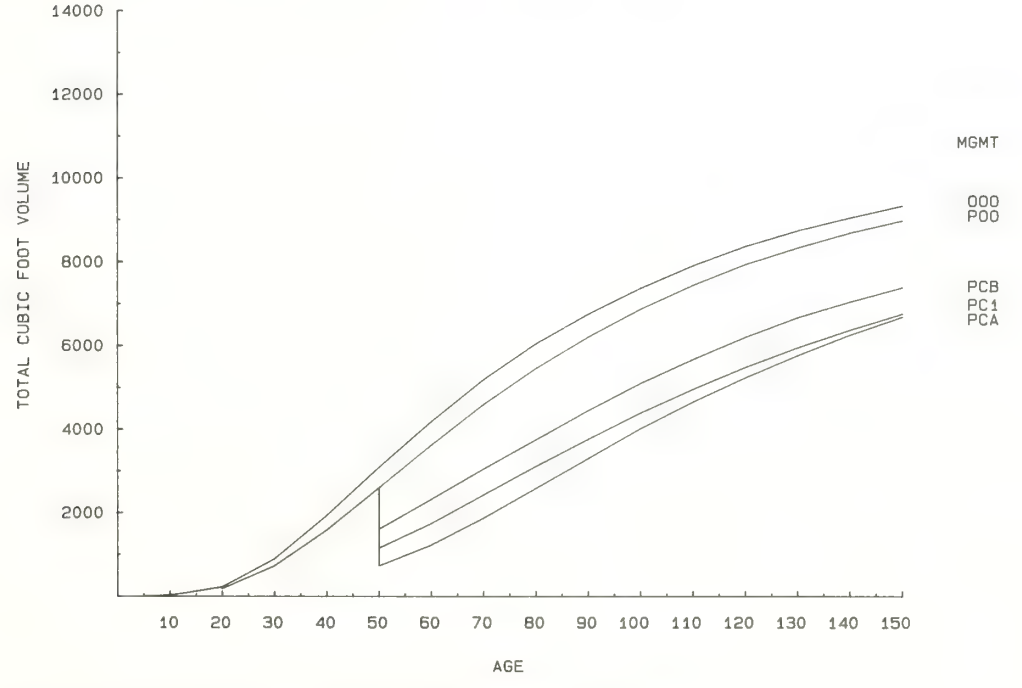


Figure 18—Effect of thinning on standing volume of Douglas-fir plantations (total cubic feet), site index 70.

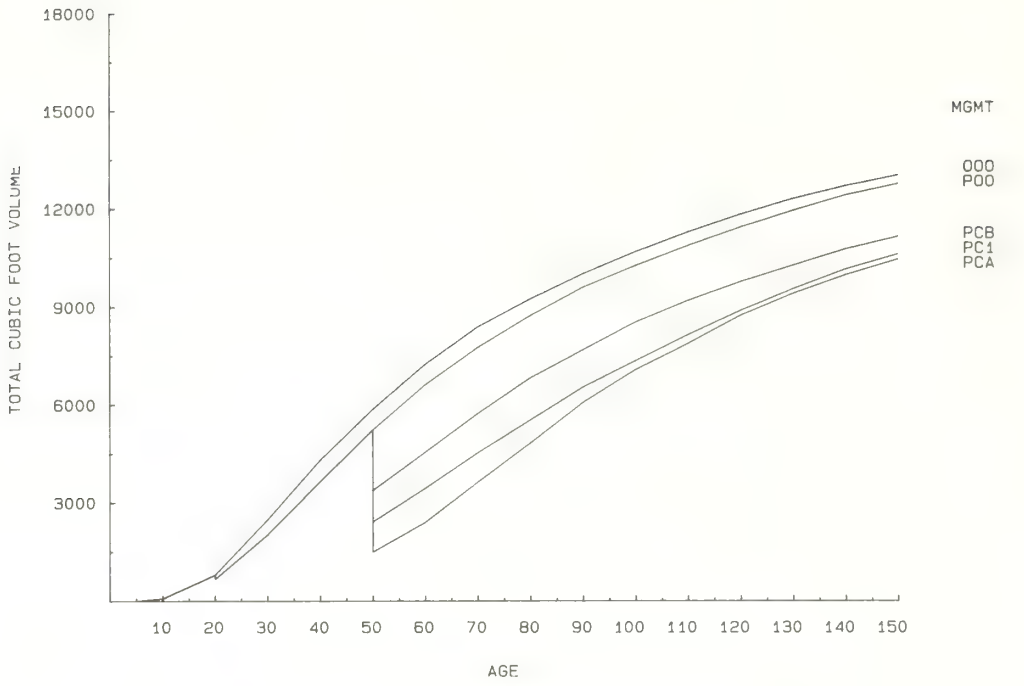


Figure 19—Effect of thinning on standing volume of Douglas-fir plantations (total cubic feet), site index 90.

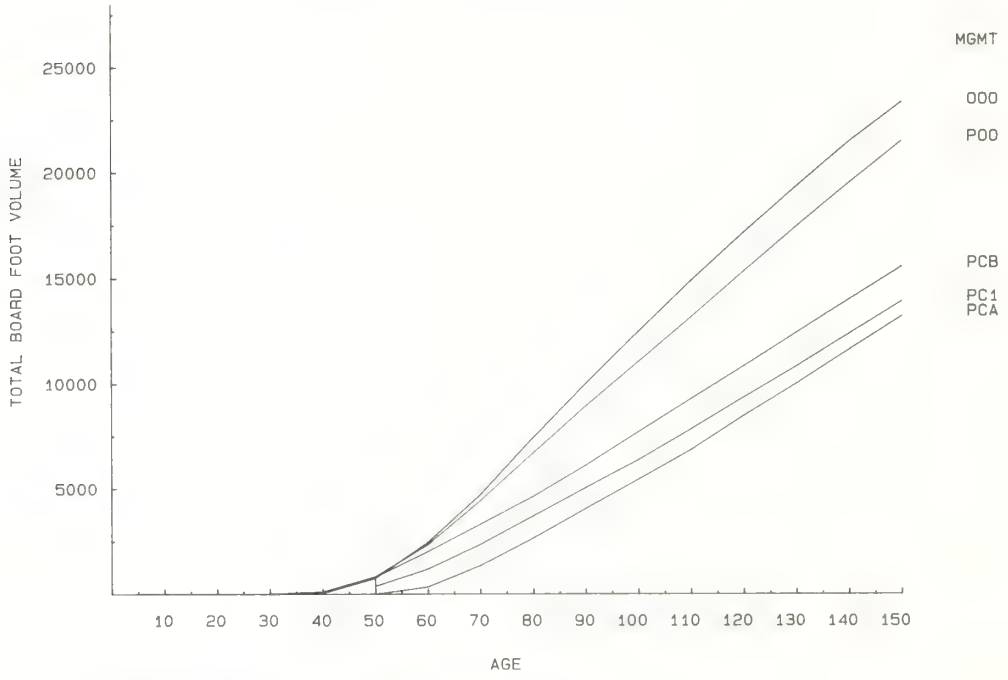


Figure 20—Effect of thinning on standing volume of Douglas-fir plantations (merchantable board feet [Scribner]), site index 50.

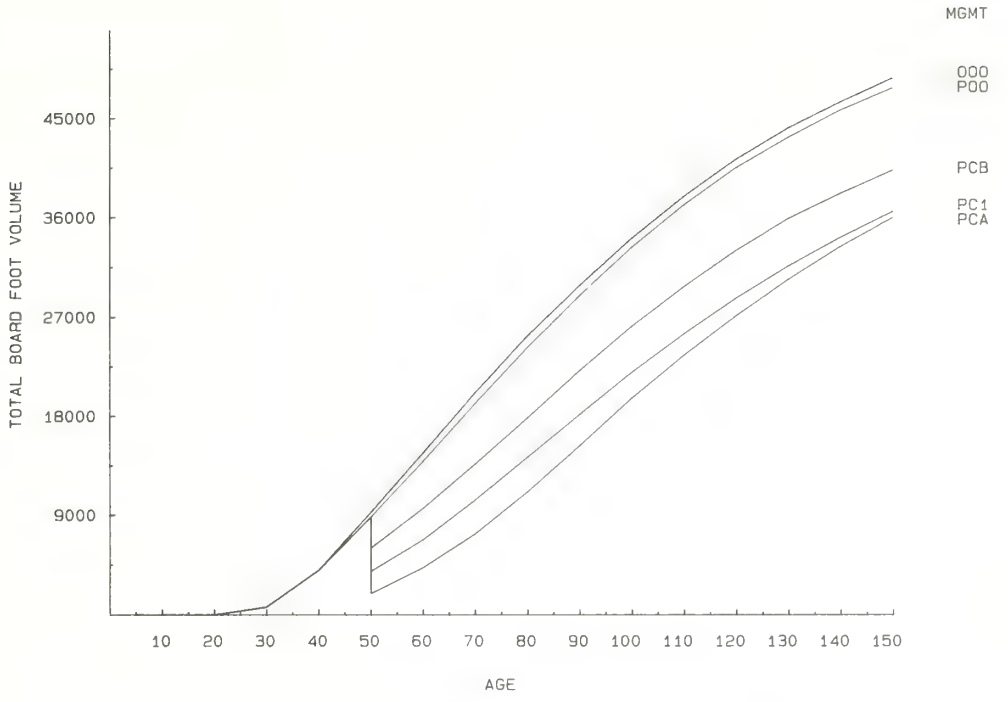


Figure 21—Effect of thinning on standing volume of Douglas-fir plantations (merchantable board feet [Scribner]), site index 70.

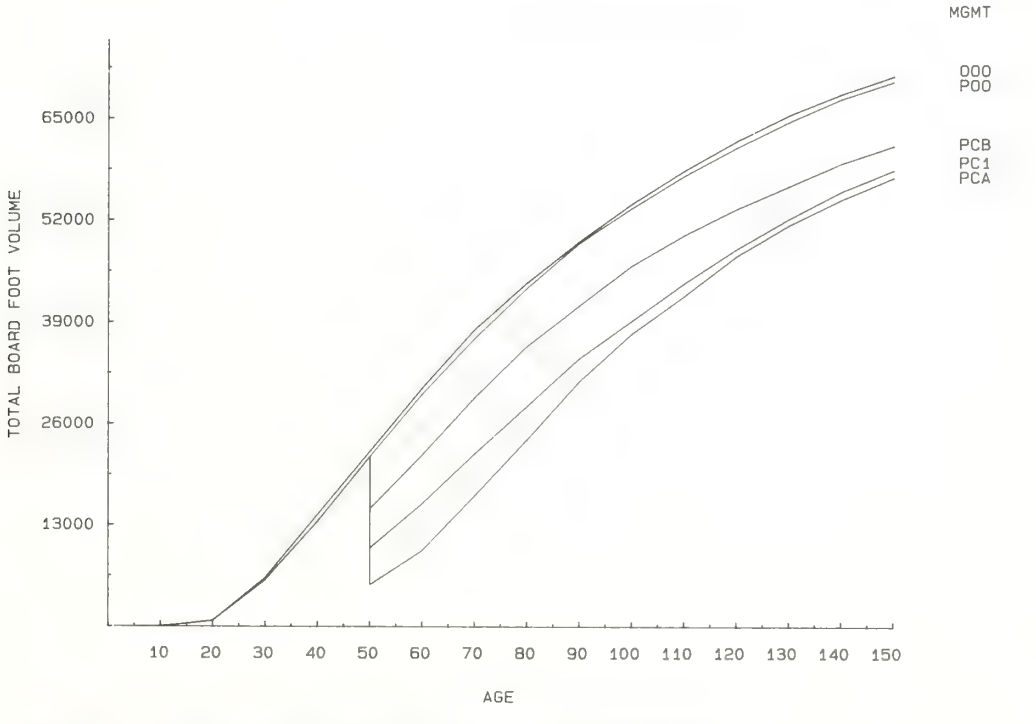


Figure 22—Effect of thinning on standing volume of Douglas-fir plantations (merchantable board feet [Scribner]), site index 90.

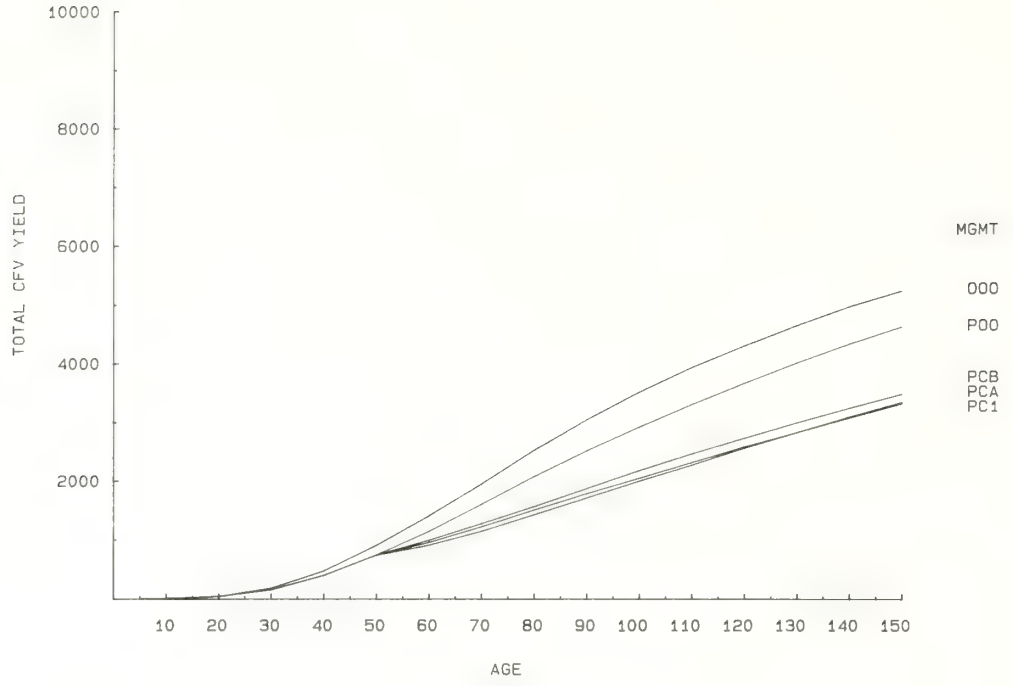


Figure 23—Effect of thinning on total yield of Douglas-fir plantations (total cubic feet), site index 50.

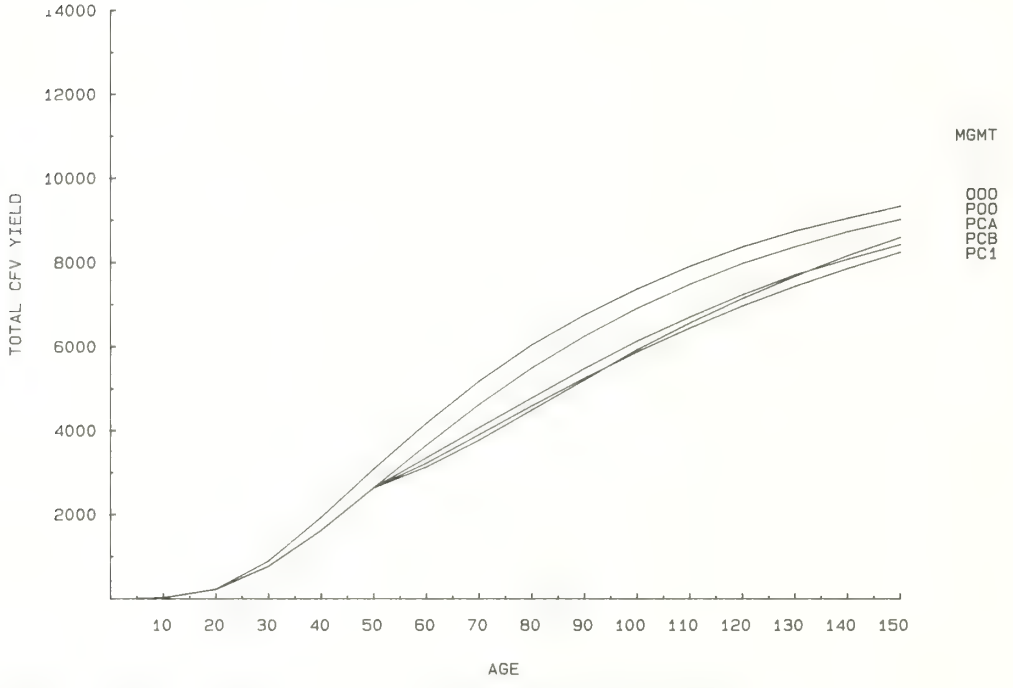


Figure 24—Effect of thinning on total yield of Douglas-fir plantations (total cubic feet), site index 70.

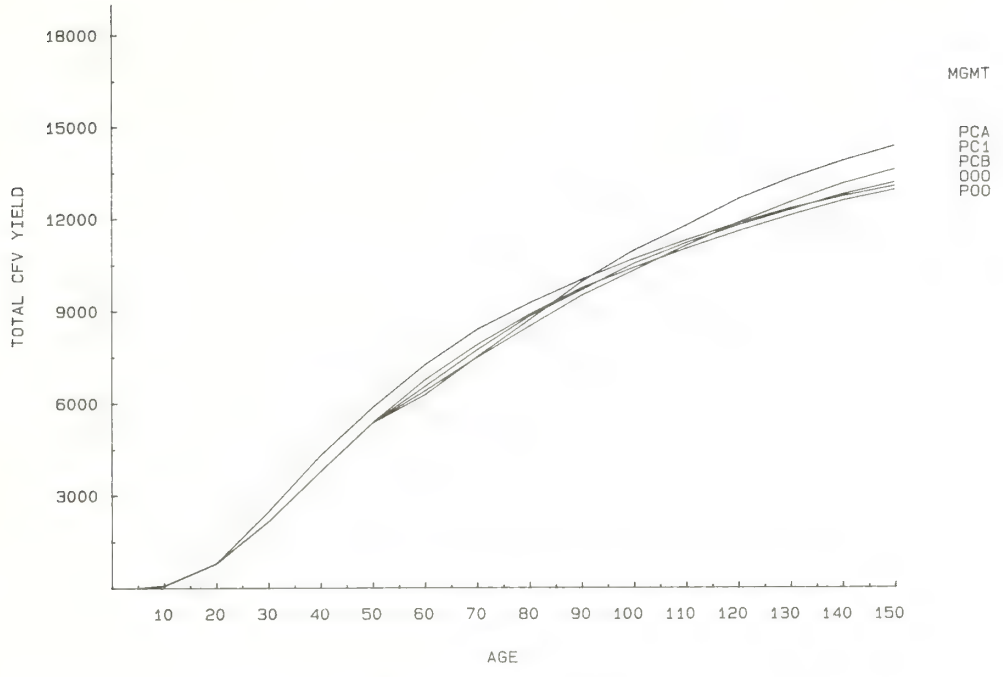


Figure 25—Effect of thinning on total yield of Douglas-fir plantations (total cubic feet), site index 90.

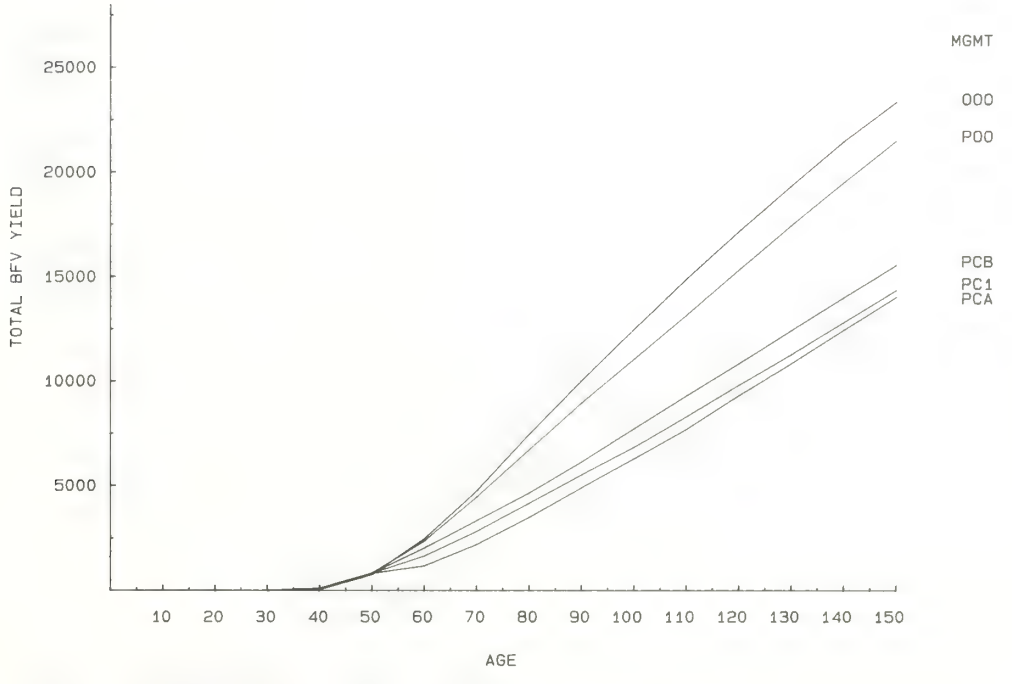


Figure 26—Effect of thinning on total yield of Douglas-fir plantations (merchantable board feet [Scribner]), site index 50.

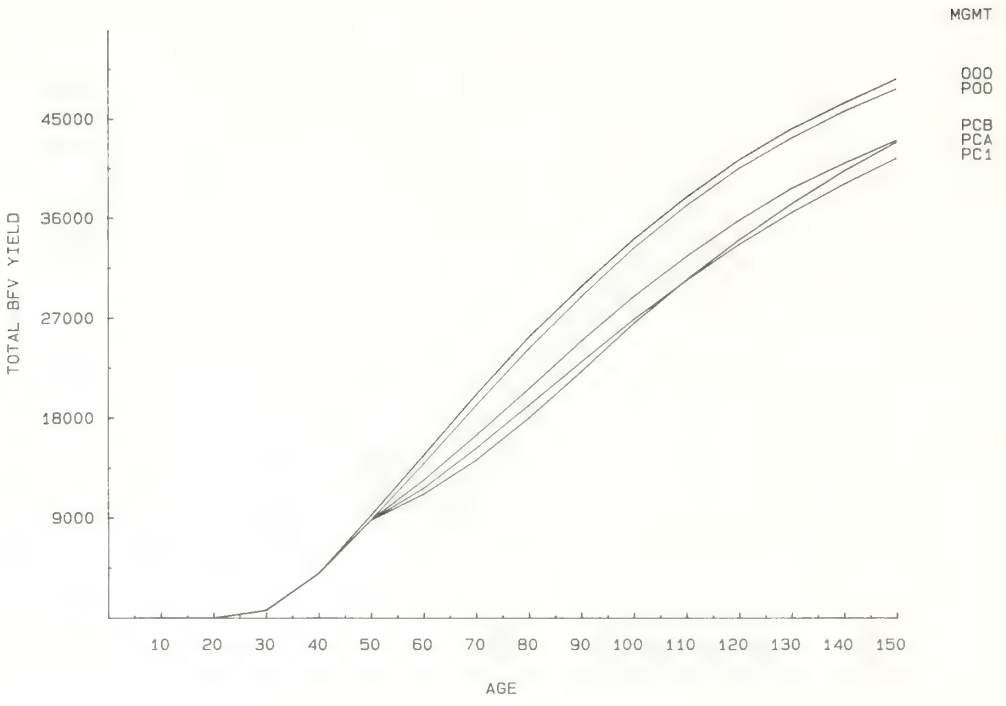


Figure 27—Effect of thinning on total yield of Douglas-fir plantations (merchantable board feet [Scribner]), site index 70.

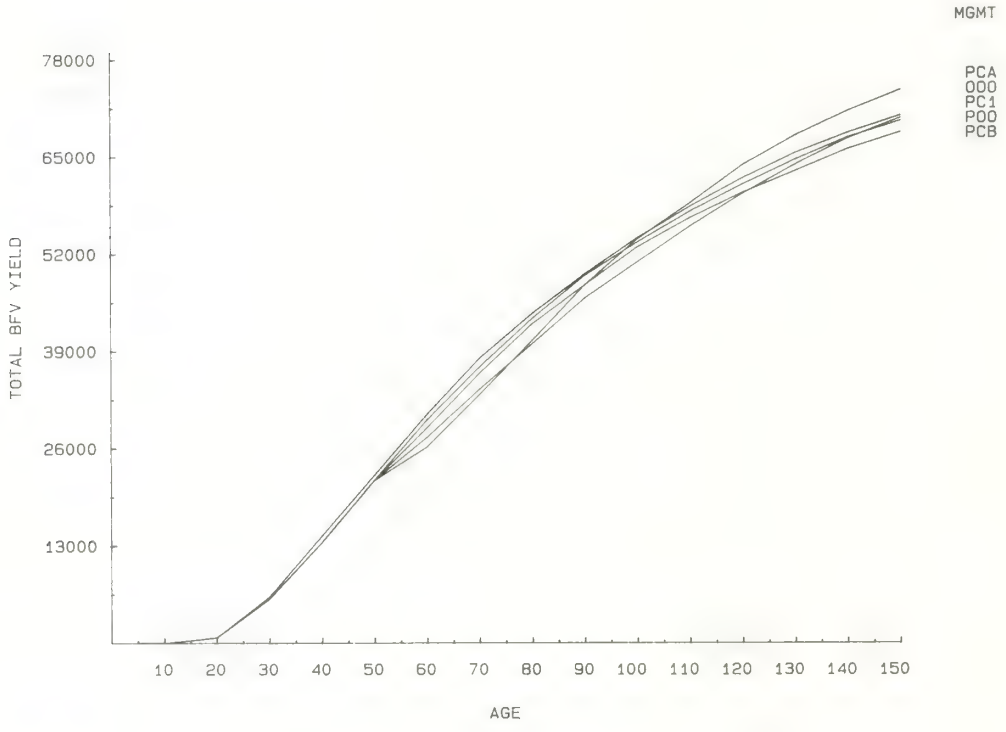


Figure 28—Effect of thinning on total yield of Douglas-fir plantations (merchantable board feet [Scribner]), site index 90.

Grand fir

Yields are summarized in tables 7 through 11 and figures 29 through 31.

In comparison to Douglas-fir plantations, early yields are lower for grand fir, but by 100 years the grand fir yields are higher for all site index classes.

Site indices for the simulations (figs. 32, 33) of grand fir plantations are lower than for either the natural regeneration simulations or for the Douglas-fir plantations. The differences are attributable to data for initial heights at age 5 represented in the Regeneration Establishment Model. Planting effect in the initial height estimation equation gives little height advantage to planted grand fir compared to Douglas-fir.

Mean d.b.h. of the grand fir plantations starts slower than Douglas-fir but surpasses it in later years (figs. 34 through 38). Grand fir plantations always have trees of larger diameter than the naturally regenerated stands, which also contain a substantial proportion of grand fir.

Effects of thinning regimes on standing volume are compared in figures 39 through 44. Effects of thinnings on total yield are compared in figures 45 through 50.

Table 7—Yields of grand fir plantations having 500 trees per acre surviving 5 years, no thinning

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	D
			Ft^3	Ft^3	Bd ft		Ft^3	Ft^3	Bd ft	Ft^2		Ft	Yr	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	2	1	5	0	0	0.0
	10	447	2	0	0	0	0	0	0	1	3	6	10	1	0	0.6
	20	371	13	0	0	0	0	0	0	3	8	12	10	7	0	1.2
	30	316	79	0	0	0	0	0	0	11	23	21	10	23	0	2.5
	40	292	308	48	160	0	0	0	0	28	52	29	10	58	1	4.2
	50	276	872	439	1546	0	0	0	0	61	100	37	10	92	4	6.4
	60	262	1758	1378	5139	0	0	0	0	100	147	45	10	125	10	8.4
	70	246	2910	2601	10567	0	0	0	0	139	184	55	10	145	19	10.2
	80	229	4166	3899	17125	0	0	0	0	171	211	64	10	157	31	11.7
	90	210	5430	5172	24275	0	0	0	0	197	230	72	10	172	45	13.1
	100	192	6700	6443	31752	0	0	0	0	218	243	79	10	177	55	14.4
	110	174	7916	7656	38998	0	0	0	0	234	253	87	10	182	67	15.7
	120	158	9072	8809	45868	0	0	0	0	247	260	93	10	182	77	16.9
	130	143	10126	9862	52038	0	0	0	0	256	264	100	10	185	86	18.1
	140	130	11108	10844	57695	0	0	0	0	263	266	105	10	182	92	19.3
	150	118	12004	11741	62725	0	0	0	0	267	266	111	0	0	0	20.4
70	5	500	0	0	0	0	0	0	0	0	2	2	5	1	0	0.0
	10	454	4	0	0	0	0	0	0	2	5	7	10	4	0	0.8
	20	393	43	0	0	0	0	0	0	7	16	17	10	25	0	1.8
	30	344	292	31	107	0	0	0	0	27	53	30	10	93	1	3.8
	40	328	1216	735	2580	0	0	0	0	80	129	41	10	176	4	6.7
	50	312	2934	2543	9929	0	0	0	0	150	207	53	10	247	21	9.4
	60	289	5203	4852	21466	0	0	0	0	216	265	65	10	268	51	11.7
	70	259	7374	7038	33865	0	0	0	0	262	299	76	10	277	82	13.6
	80	228	9329	8997	45454	0	0	0	0	291	318	84	10	307	114	15.3
	90	198	11255	10921	56820	0	0	0	0	313	329	93	10	298	130	17.0
	100	174	12935	12603	66608	0	0	0	0	327	334	101	10	316	155	18.6
	110	151	14543	14211	75669	0	0	0	0	337	336	109	10	307	163	20.2
	120	133	15989	15658	83652	0	0	0	0	344	337	116	10	296	168	21.8
	130	118	17271	16942	90581	0	0	0	0	348	335	123	10	289	175	23.3
	140	105	18408	18083	96624	0	0	0	0	350	332	129	10	294	182	24.8
	150	93	19534	19210	102513	0	0	0	0	352	330	135	0	0	0	26.3
90	5	500	0	0	0	0	0	0	0	0	2	3	5	1	0	0.0
	10	459	6	0	0	0	0	0	0	2	6	8	10	8	0	1.0
	20	406	80	0	0	0	0	0	0	11	24	21	10	64	0	2.2
	30	366	717	321	1175	0	0	0	0	55	91	36	10	208	1	5.2
	40	351	2789	2335	9459	0	0	0	0	149	206	55	10	347	17	8.8
	50	323	6086	5695	26543	0	0	0	0	252	302	70	10	400	67	12.0
	60	284	9408	8994	44885	0	0	0	0	319	354	85	10	352	120	14.4
	70	245	11718	11324	58472	0	0	0	0	353	377	91	10	428	174	16.3
	80	207	14256	13869	73051	0	0	0	0	379	387	100	10	374	187	18.3
	90	178	16122	15735	83469	0	0	0	0	391	390	110	10	431	237	20.1
	100	150	18068	17689	94258	0	0	0	0	401	390	117	10	417	239	22.1
	110	129	19846	19469	103758	0	0	0	0	407	388	124	10	376	231	24.0
	120	113	21302	20927	111471	0	0	0	0	410	385	130	10	367	236	25.7
	130	101	22611	22240	118360	0	0	0	0	412	382	136	10	386	246	27.4
	140	89	24022	23651	125692	0	0	0	0	415	379	142	10	388	256	29.2
	150	79	25343	24974	132570	0	0	0	0	417	377	148	0	0	0	31.0

Table 8—Yields of grand fir plantations having 500 trees per acre surviving 5 years, precommercial thinning from below to 250 trees per acre at 20 years

Site index	Age	Trees/ acre	Summary statistics: Volume per acre: Total volume	Merchantable volume	Merchantable volume	Removals per acre: Trees/ acre	Total volume	Merchantable volume	Merchantable volume	BA/ acre	CCF	Top height	Growth: PRD	ACC	MOR/ year	$\bar{D}$
			Ft³	*Ft³*	*Bd ft*		*Ft³*	*Ft³*	*Bd ft*	*Ft²*		*Ft*	*Yr*	*Ft³*	*Ft³*	
50	5	500	0	0	0	0	0	0	0	0	2	1	5	0	0	0.0
	10	447	2	0	0	0	0	0	0	1	3	6	10	1	0	0.6
	20	371	13	0	0	121	1	0	0	3	7	12	10	6	0	1.4
	30	216	70	0	0	0	0	0	0	9	19	21	10	21	0	2.8
	40	204	278	57	189	0	0	0	0	24	44	29	10	51	1	4.7
	50	194	776	458	1617	0	0	0	0	52	82	37	10	84	2	7.0
	60	186	1593	1344	5146	0	0	0	0	86	121	47	10	112	7	9.2
	70	178	2644	2444	10267	0	0	0	0	119	152	56	10	134	15	11.1
	80	167	3839	3645	16635	0	0	0	0	149	176	65	10	148	24	12.8
	90	156	5074	4871	23646	0	0	0	0	174	195	73	10	158	35	14.3
	100	145	6303	6090	30847	0	0	0	0	195	210	81	10	166	46	15.7
	110	133	7509	7287	37917	0	0	0	0	212	222	88	10	169	56	17.1
	120	123	8642	8413	44488	0	0	0	0	225	231	95	10	172	66	18.3
	130	113	9707	9474	50532	0	0	0	0	235	237	101	10	174	74	19.6
	140	103	10713	10476	56107	0	0	0	0	243	241	107	10	173	80	20.8
	150	95	11643	11404	61157	0	0	0	0	249	244	113	0	0	0	21.9
70	5	500	0	0	0	0	0	0	0	0	2	2	5	1	0	0.0
	10	454	4	0	0	0	0	0	0	2	5	7	10	4	0	0.8
	20	393	43	0	0	143	4	0	0	6	13	17	10	21	0	2.1
	30	227	252	23	75	0	0	0	0	22	42	30	10	81	0	4.3
	40	220	1051	678	2415	0	0	0	0	66	104	41	10	152	3	7.4
	50	213	2541	2298	9110	0	0	0	0	123	163	53	10	206	12	10.3
	60	202	4472	4244	19060	0	0	0	0	177	210	64	10	248	33	12.7
	70	186	6623	6373	31436	0	0	0	0	223	247	75	10	280	60	14.8
	80	169	8819	8547	44298	0	0	0	0	260	274	85	10	273	81	16.8
	90	153	10735	10449	55334	0	0	0	0	284	291	94	10	294	112	18.5
	100	136	12566	12270	65600	0	0	0	0	303	302	103	10	281	124	20.2
	110	121	14136	13836	74108	0	0	0	0	315	308	110	10	289	140	21.8
	120	109	15632	15327	82140	0	0	0	0	324	312	117	10	284	149	23.4
	130	98	16985	16679	89283	0	0	0	0	331	314	124	10	278	158	24.9
	140	88	18190	17884	95577	0	0	0	0	335	314	131	10	280	164	26.4
	150	80	19349	19042	101548	0	0	0	0	339	314	137	0	0	0	28.0
90	5	500	0	0	0	0	0	0	0	0	2	3	5	1	0	0.0
	10	459	6	0	0	0	0	0	0	2	6	8	10	8	0	1.0
	20	406	80	0	0	156	8	0	0	10	20	21	10	57	0	2.6
	30	235	635	281	1027	0	0	0	0	46	74	36	10	207	1	6.0
	40	229	2696	2438	10450	0	0	0	0	133	176	55	10	371	13	10.3
	50	216	6268	5998	29285	0	0	0	0	233	263	74	10	283	47	14.0
	60	199	8634	8333	42318	0	0	0	0	280	299	84	10	460	110	16.1
	70	172	12127	11797	61876	0	0	0	0	333	339	96	10	401	146	18.8
	80	151	14685	14340	75913	0	0	0	0	362	356	107	10	359	169	21.0
	90	133	16585	16233	86302	0	0	0	0	376	363	113	10	397	203	22.8
	100	116	18522	18166	96700	0	0	0	0	387	366	122	10	374	207	24.8
	110	101	20182	19826	105655	0	0	0	0	393	366	128	10	407	234	26.7
	120	90	21914	21556	114805	0	0	0	0	400	367	135	10	340	208	28.6
	130	81	23229	22870	121656	0	0	0	0	404	368	141	10	385	240	30.3
	140	72	24677	24317	129187	0	0	0	0	408	367	146	10	387	245	32.1
	150	64	26094	25734	136479	0	0	0	0	411	365	153	0	0	0	34.2

Table 9—Yields of grand fir plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning from below to 100 trees per acre at 50 years

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
				Ft³	*Ft³*	*Bd ft*		*Ft³*	*Ft³*	*Bd ft*	*Ft²*		*Ft*	*Yr*	*Ft³*	*Ft³*
50	5	500	0	0	0	0	0	0	0	0	2	1	5	0	0	0.0
	10	447	2	0	0	0	0	0	0	1	3	6	10	1	0	0.6
	20	371	13	0	0	121	1	0	0	3	7	12	10	6	0	1.4
	30	216	70	0	0	0	0	0	0	9	19	21	10	21	0	2.8
	40	204	278	57	189	0	0	0	0	24	44	29	10	51	1	4.7
	50	194	776	458	1617	94	207	40	133	36	55	37	10	60	1	8.1
	60	98	1163	1062	4193	0	0	0	0	59	78	47	10	82	3	10.5
	70	95	1946	1844	8115	0	0	0	0	82	98	57	10	100	7	12.6
	80	91	2876	2759	13289	0	0	0	0	105	117	66	10	118	13	14.5
	90	87	3928	3794	19360	0	0	0	0	126	135	75	10	124	19	16.3
	100	83	4978	4832	25413	0	0	0	0	144	150	82	10	135	27	17.9
	110	78	6061	5904	31489	0	0	0	0	161	162	90	10	145	34	19.4
	120	73	7169	7000	37568	0	0	0	0	175	174	97	10	140	39	20.9
	130	69	8180	8004	43020	0	0	0	0	187	182	104	10	150	48	22.3
	140	65	9195	9011	48389	0	0	0	0	198	190	110	10	150	53	23.6
	150	61	10169	9978	53514	0	0	0	0	207	196	116	0	0	0	24.9
70	5	500	0	0	0	0	0	0	0	0	2	2	5	1	0	0.0
	10	454	4	0	0	0	0	0	0	2	5	7	10	4	0	0.8
	20	393	43	0	0	143	4	0	0	6	13	17	10	21	0	2.1
	30	227	252	23	75	0	0	0	0	22	42	30	10	81	0	4.3
	40	220	1051	678	2415	0	0	0	0	66	104	41	10	152	3	7.4
	50	213	2541	2298	9110	113	819	674	2405	80	96	53	10	144	4	12.1
	60	98	3121	2994	14329	0	0	0	0	117	130	65	10	190	12	14.8
	70	94	4901	4745	24711	0	0	0	0	155	162	76	10	209	24	17.4
	80	89	6747	6566	35163	0	0	0	0	187	189	86	10	239	43	19.6
	90	83	8703	8500	45783	0	0	0	0	217	212	96	10	235	54	21.8
	100	78	10506	10285	55350	0	0	0	0	239	230	105	10	252	75	23.7
	110	72	12275	12040	64575	0	0	0	0	259	244	112	10	265	91	25.6
	120	67	14008	13761	73554	0	0	0	0	275	256	121	10	251	98	27.5
	130	62	15547	15290	81522	0	0	0	0	288	265	127	10	249	110	29.2
	140	57	16936	16672	88727	0	0	0	0	298	271	134	10	239	118	30.8
	150	53	18155	17887	95029	0	0	0	0	305	275	139	0	0	0	32.3
90	5	500	0	0	0	0	0	0	0	0	2	3	5	1	0	0.0
	10	459	6	0	0	0	0	0	0	2	6	8	10	8	0	1.0
	20	406	80	0	0	156	8	0	0	10	20	21	10	57	0	2.6
	30	235	635	281	1027	0	0	0	0	46	74	36	10	207	1	6.0
	40	229	2696	2438	10450	0	0	0	0	133	176	55	10	371	13	10.3
	50	216	6268	5998	29285	116	1367	1262	4808	168	175	74	10	249	18	17.5
	60	96	7205	7005	37270	0	0	0	0	211	212	86	10	278	42	20.1
	70	91	9578	9349	50117	0	0	0	0	248	241	97	10	355	73	22.4
	80	83	12392	12134	65093	0	0	0	0	285	270	108	10	400	109	25.1
	90	76	15299	15015	80242	0	0	0	0	319	296	117	10	431	148	27.8
	100	69	18135	17831	95001	0	0	0	0	345	314	126	10	436	183	30.3
	110	61	20666	20347	108111	0	0	0	0	364	327	134	10	349	172	33.0
	120	57	22427	22101	117243	0	0	0	0	375	333	142	10	320	172	34.9
	130	52	23903	23573	124896	0	0	0	0	382	336	147	10	248	155	36.7
	140	49	24840	24510	129748	0	0	0	0	383	335	151	10	304	199	38.0
	150	44	25894	25564	135201	0	0	0	0	384	334	156	0	0	0	39.9

Table 10—Yields of grand fir plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning from above to 100 trees per acre at 50 years

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
				Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3
50	5	500	0	0	0	0	0	0	0	0	2	1	5	0	0	0.0
	10	447	2	0	0	0	0	0	0	1	3	6	10	1	0	0.6
	20	371	13	0	0	121	1	0	0	3	7	12	10	6	0	1.4
	30	216	70	0	0	0	0	0	0	9	19	21	10	21	0	2.8
	40	204	278	57	189	0	0	0	0	24	44	29	10	51	1	4.7
	50	194	776	458	1617	94	557	422	1499	17	29	31	10	36	1	5.6
	60	96	573	422	1489	0	0	0	0	34	52	40	10	59	1	8.0
	70	93	1147	1045	4108	0	0	0	0	55	73	50	10	79	3	10.4
	80	90	1905	1804	7966	0	0	0	0	76	92	60	10	99	7	12.5
	90	87	2823	2710	13092	0	0	0	0	98	110	69	10	114	12	14.4
	100	83	3845	3718	19000	0	0	0	0	119	127	78	10	129	18	16.2
	110	79	4950	4809	25310	0	0	0	0	138	143	86	10	139	24	17.9
	120	75	6097	5944	31716	0	0	0	0	155	157	94	10	137	31	19.5
	130	71	7155	6992	37516	0	0	0	0	169	168	101	10	143	40	21.0
	140	66	8178	8006	43020	0	0	0	0	181	176	107	10	148	46	22.4
	150	62	9202	9023	48447	0	0	0	0	192	184	113	0	0	0	23.7
70	5	500	0	0	0	0	0	0	0	0	2	2	5	1	0	0.0
	10	454	4	0	0	0	0	0	0	2	5	7	10	4	0	0.8
	20	393	43	0	0	143	4	0	0	6	13	17	10	21	0	2.1
	30	227	252	23	75	0	0	0	0	22	42	30	10	81	0	4.3
	40	220	1051	678	2415	0	0	0	0	66	104	41	10	152	3	7.4
	50	213	2541	2298	9110	113	1862	1752	7185	37	57	45	10	91	2	8.2
	60	96	1571	1470	5978	0	0	0	0	66	84	58	10	145	4	11.2
	70	94	2979	2860	13740	0	0	0	0	103	115	69	10	190	10	14.1
	80	90	4785	4638	24083	0	0	0	0	141	148	82	10	228	23	16.9
	90	86	6838	6663	35595	0	0	0	0	177	179	93	10	251	39	19.4
	100	81	8961	8762	47095	0	0	0	0	208	205	102	10	245	54	21.7
	110	76	10868	10652	57206	0	0	0	0	233	224	111	10	242	71	23.7
	120	71	12583	12353	66225	0	0	0	0	251	237	119	10	238	82	25.5
	130	66	14146	13905	74315	0	0	0	0	266	247	126	10	265	108	27.1
	140	61	15720	15470	82470	0	0	0	0	279	256	133	10	251	111	28.9
	150	57	17126	16870	89740	0	0	0	0	289	262	138	0	0	0	30.6
90	5	500	0	0	0	0	0	0	0	0	2	3	5	1	0	0.0
	10	459	6	0	0	0	0	0	0	2	6	8	10	8	0	1.0
	20	406	80	0	0	156	8	0	0	10	20	21	10	57	0	2.6
	30	235	635	281	1027	0	0	0	0	46	74	36	10	207	1	6.0
	40	229	2696	2438	10450	0	0	0	0	133	176	55	10	371	13	10.3
	50	216	6268	5998	29285	116	5190	5009	25605	52	73	52	10	123	3	9.8
	60	97	2278	2171	9531	0	0	0	0	87	103	65	10	181	5	12.9
	70	95	4038	3903	19850	0	0	0	0	127	138	80	10	306	17	15.7
	80	90	6932	6754	36266	0	0	0	0	182	185	94	10	379	38	19.3
	90	85	10345	10125	54574	0	0	0	0	236	229	109	10	374	69	22.6
	100	79	13391	13141	70416	0	0	0	0	274	261	119	10	320	94	25.2
	110	73	15645	15377	82187	0	0	0	0	297	277	128	10	341	125	27.3
	120	67	17801	17518	93313	0	0	0	0	318	291	135	10	275	117	29.5
	130	62	19386	19095	101522	0	0	0	0	329	299	141	10	293	145	31.1
	140	57	20864	20567	109179	0	0	0	0	338	303	147	10	361	171	32.8
	150	53	22768	22463	119047	0	0	0	0	350	311	154	0	0	0	34.9

Table 11—Yields of grand fir plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning to 100 trees per acre at 50 years such that the mean d.b.h. before and after thinning is the same

			Summary statistics														
			Volume per acre			Removals per acre							Growth				
Site index	Age	Trees acre	Total volume	Merchantable volume	Merchantable volume	Trees/ acre	Total volume	Merchantable volume	Merchantable volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	D	
				Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	2	1	5	0	0	0.0	
	10	447	2	0	0	0	0	0	0	1	3	6	10	1	0	0.6	
	20	371	13	0	0	121	1	0	0	3	7	12	10	6	0	1.4	
	30	216	70	0	0	0	0	0	0	9	19	21	10	21	0	2.8	
	40	204	278	57	189	0	0	0	0	24	44	29	10	51	1	4.7	
	50	194	776	458	1617	94	380	227	800	27	42	36	10	48	1	7.0	
	60	97	870	743	2856	0	0	0	0	46	64	45	10	70	2	9.4	
	70	94	1544	1442	6152	0	0	0	0	68	85	55	10	90	5	11.5	
	80	91	2398	2288	10710	0	0	0	0	90	104	64	10	106	9	13.5	
	90	87	3364	3241	16161	0	0	0	0	112	122	72	10	119	15	15.4	
	100	83	4398	4262	22099	0	0	0	0	131	138	81	10	129	22	17.0	
	110	78	5468	5320	28159	0	0	0	0	148	151	88	10	134	28	18.6	
	120	74	6525	6366	34033	0	0	0	0	163	163	96	10	140	36	20.1	
	130	70	7567	7399	39700	0	0	0	0	176	173	102	10	143	42	21.5	
	140	65	8574	8398	45086	0	0	0	0	187	181	109	10	144	49	22.9	
	150	61	9526	9344	50130	0	0	0	0	196	187	114	0	0	0	24.2	
70	5	500	0	0	0	0	0	0	0	0	2	2	5	1	0	0.0	
	10	454	4	0	0	0	0	0	0	2	5	7	10	4	0	0.8	
	20	393	43	0	0	143	4	0	0	6	13	17	10	21	0	2.1	
	30	227	252	23	75	0	0	0	0	22	42	30	10	81	0	4.3	
	40	220	1051	678	2415	0	0	0	0	66	104	41	10	152	3	7.4	
	50	213	2541	2298	9110	113	1348	1219	4834	58	77	50	10	115	3	10.3	
	60	97	2316	2203	10037	0	0	0	0	91	106	62	10	163	7	13.1	
	70	94	3871	3735	18846	0	0	0	0	127	137	74	10	209	17	15.7	
	80	90	5792	5628	29699	0	0	0	0	164	169	85	10	210	28	18.3	
	90	85	7611	7425	39757	0	0	0	0	193	192	95	10	242	48	20.4	
	100	79	9549	9343	50145	0	0	0	0	220	214	104	10	243	63	22.5	
	110	74	11346	11124	59627	0	0	0	0	241	229	112	10	250	79	24.5	
	120	68	13059	12824	68619	0	0	0	0	258	242	120	10	236	87	26.3	
	130	64	14543	14299	76333	0	0	0	0	271	251	126	10	226	98	28.0	
	140	59	15829	15579	82985	0	0	0	0	281	257	133	10	234	111	29.5	
	150	54	17057	16801	89358	0	0	0	0	289	261	139	0	0	0	31.2	
90	5	500	0	0	0	0	0	0	0	0	2	3	5	1	0	0.0	
	10	459	6	0	0	0	0	0	0	2	6	8	10	8	0	1.0	
	20	406	80	0	0	156	8	0	0	10	20	21	10	57	0	2.6	
	30	235	635	281	1027	0	0	0	0	46	74	36	10	207	1	6.0	
	40	229	2696	2438	10450	0	0	0	0	133	176	55	10	371	13	10.3	
	50	216	6268	5998	29285	116	3373	3227	15757	107	121	66	10	171	7	14.0	
	60	97	4537	4386	22400	0	0	0	0	145	153	78	10	340	22	16.6	
	70	91	7709	7512	39671	0	0	0	0	204	203	94	10	329	42	20.2	
	80	87	10585	10355	55221	0	0	0	0	247	239	105	10	309	70	22.9	
	90	81	12978	12725	68003	0	0	0	0	278	262	114	10	338	100	25.1	
	100	74	15354	15082	80565	0	0	0	0	303	281	123	10	325	116	27.4	
	110	68	17441	17155	91438	0	0	0	0	322	295	130	10	355	142	29.5	
	120	62	19569	19271	102467	0	0	0	0	339	306	137	10	306	141	31.5	
	130	58	21215	20907	110978	0	0	0	0	351	314	143	10	344	171	33.4	
	140	53	22944	22629	119944	0	0	0	0	361	320	149	10	341	177	35.4	
	150	48	24586	24265	128454	0	0	0	0	370	325	155	0	0	0	37.5	

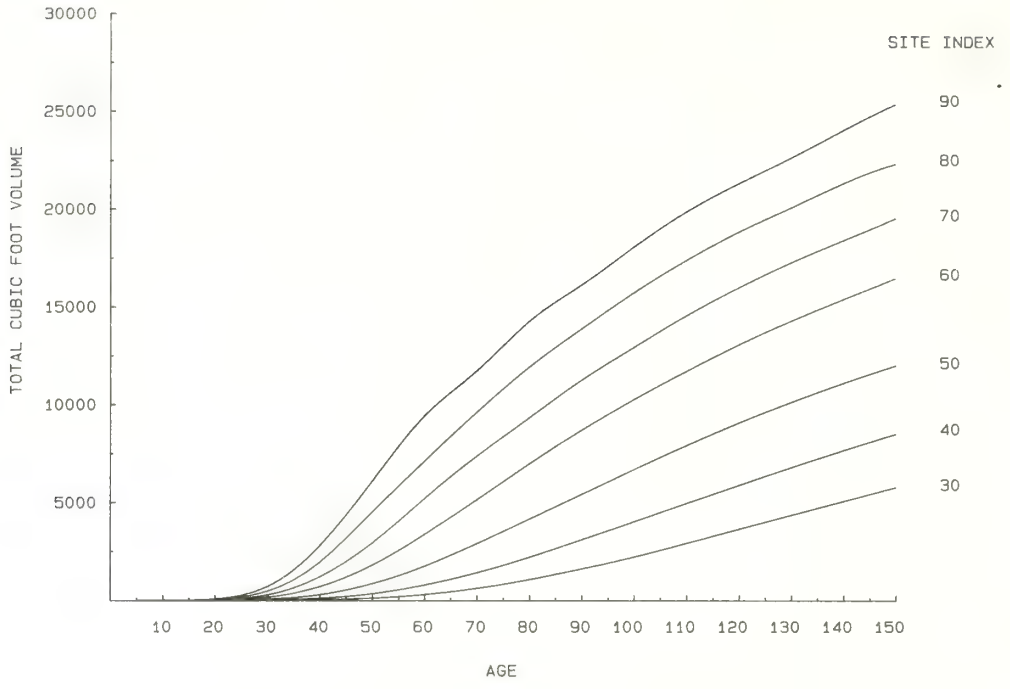


Figure 29—Grand fir yield curves for unthinned plantations in Inland Northwest forests (total cubic feet all stems).

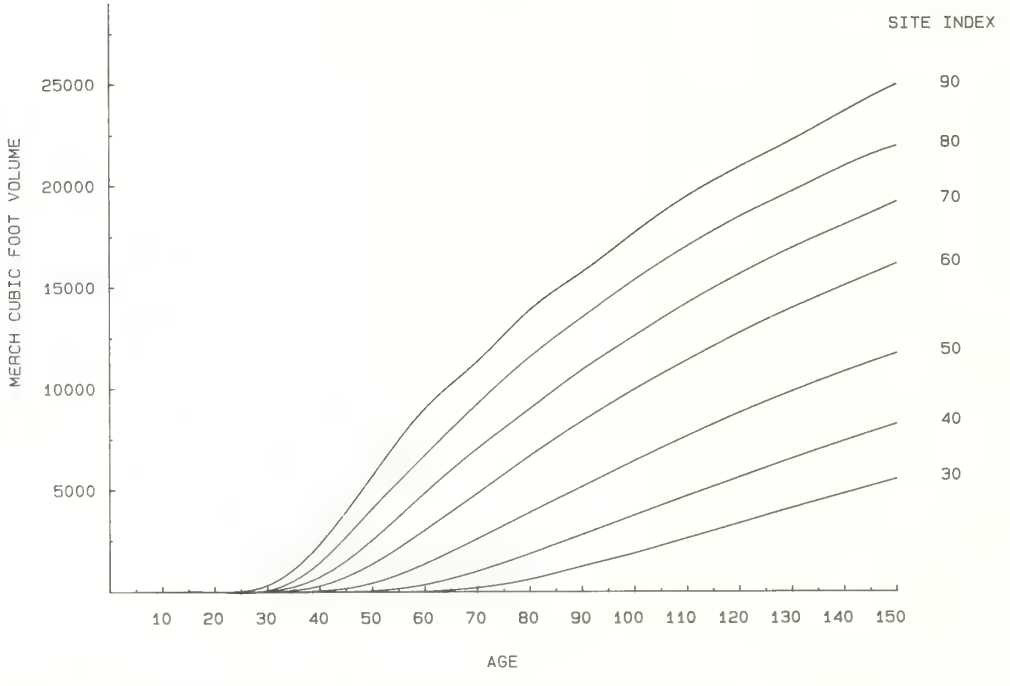


Figure 30—Grand fir yield curves for unthinned plantations in Inland Northwest forests (merchantable cubic feet, 4.5-inch top, stems greater than 7 inches d.b.h.).

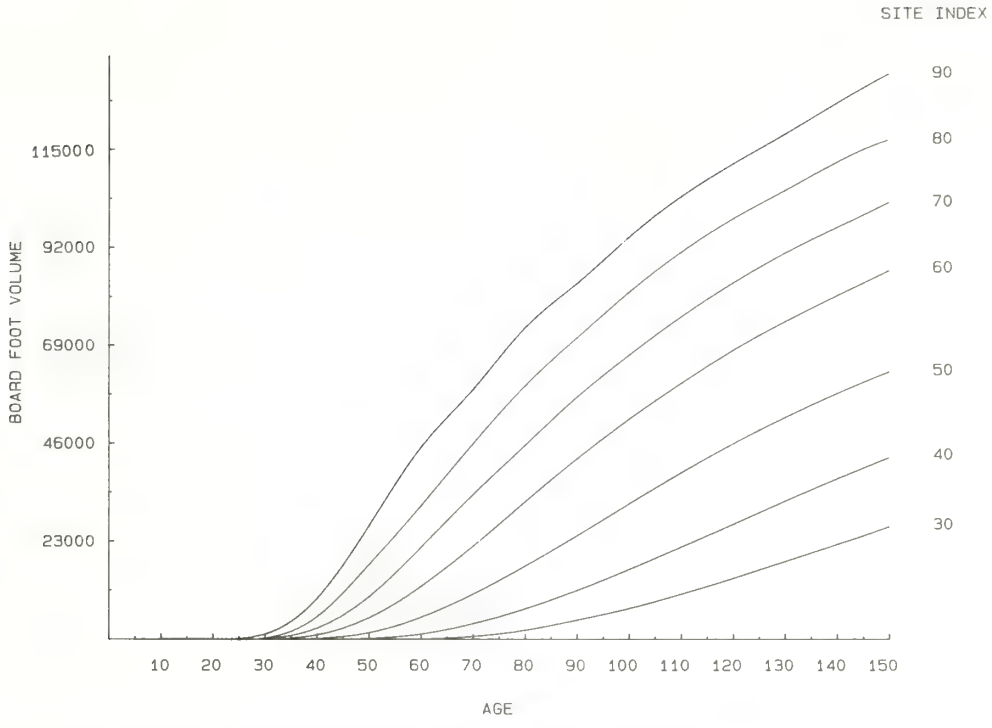


Figure 31—Grand fir yield curves for unthinned plantations in Inland Northwest forests (merchantable board feet [Scribner] 4.5-inch top, stems greater than 7 inches d.b.h.).

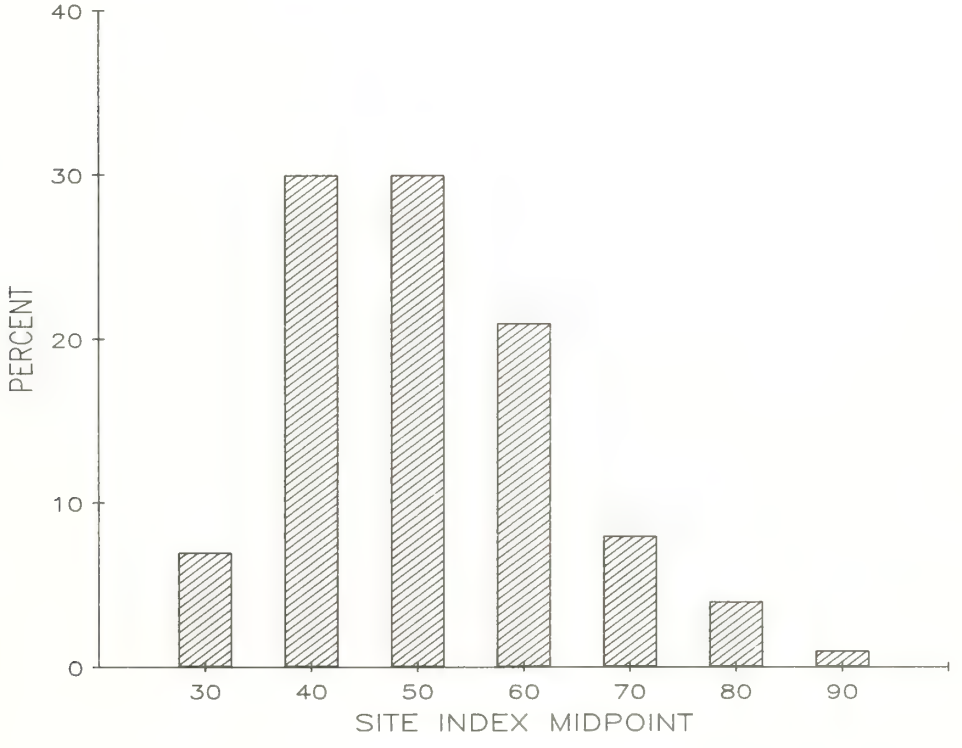


Figure 32—Distribution of grand fir plantation site index values for Inland Northwest forests.

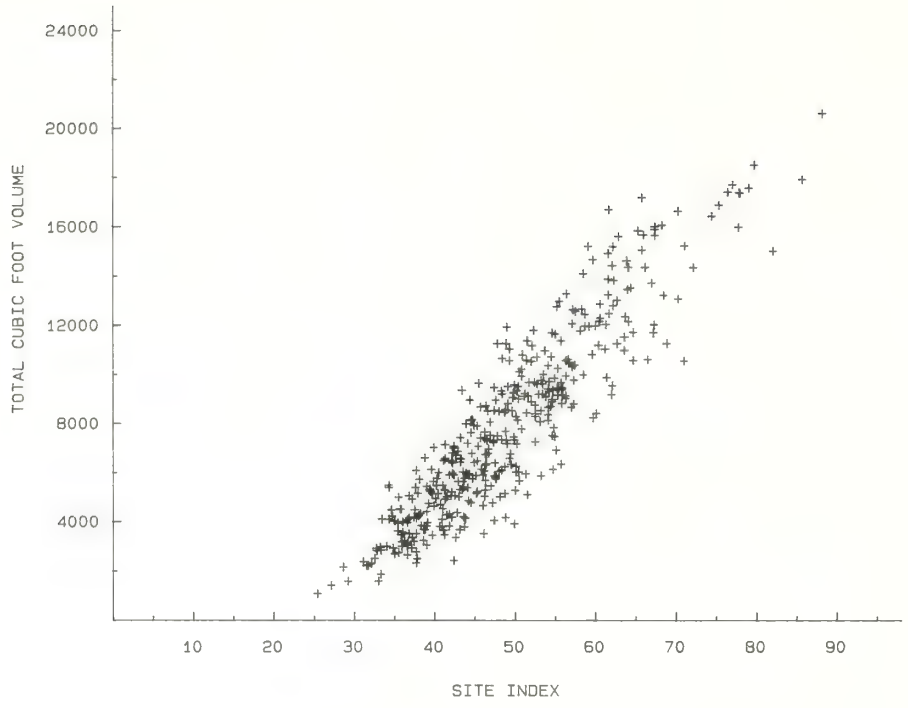


Figure 33—Grand fir yield vs. site index at 110 years (total cubic feet).

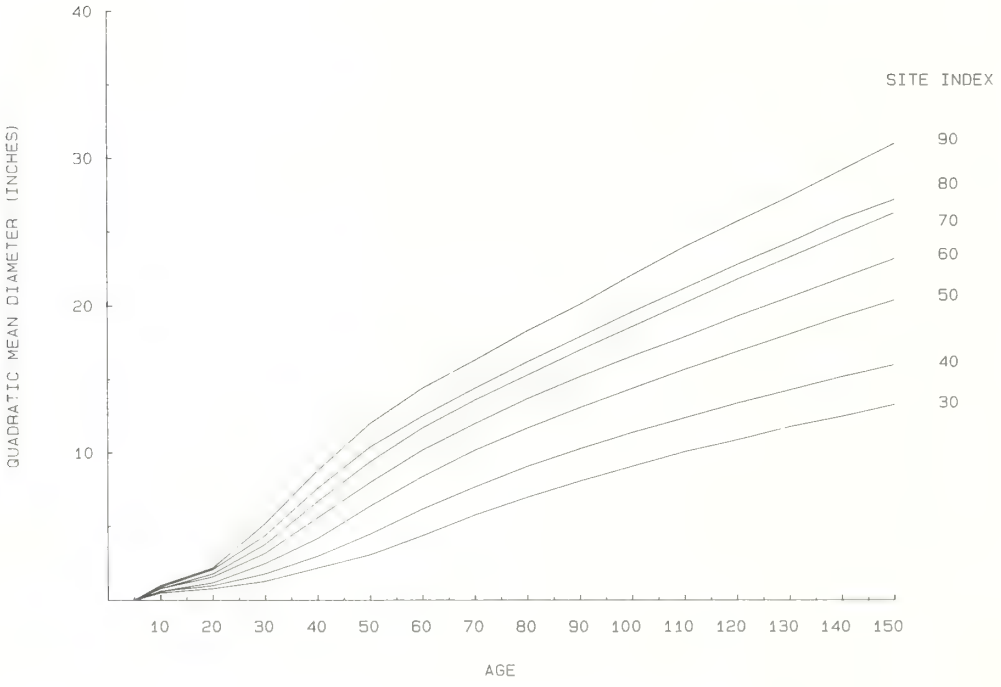


Figure 34—Quadratic mean diameter vs. age for grand fir unthinned plantations in Inland Northwest forests.

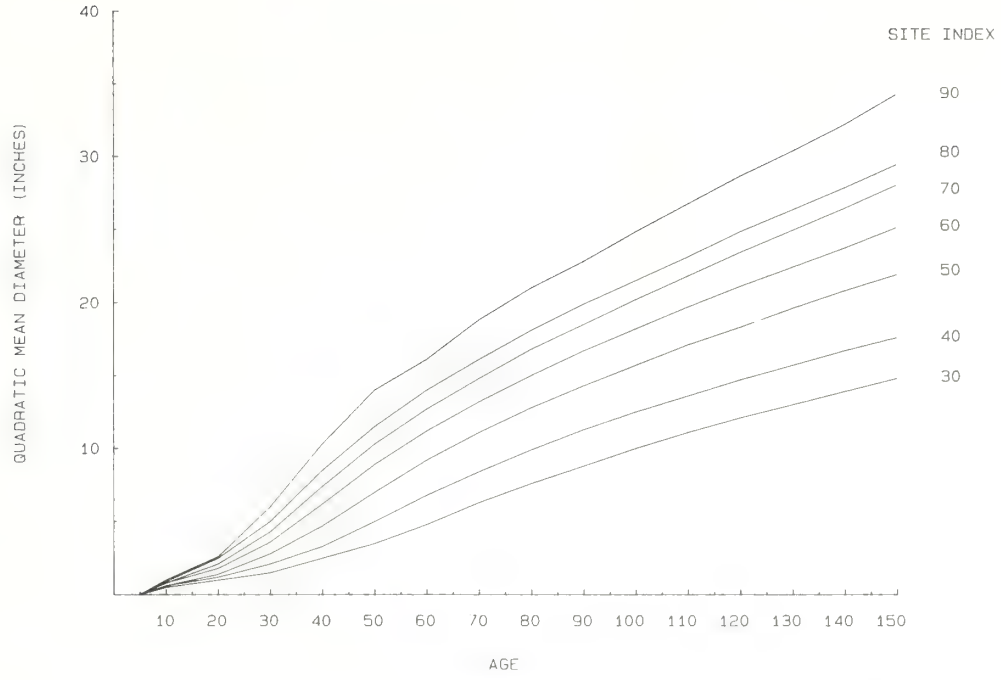


Figure 35—Quadratic mean diameter vs. age for grand fir precommercial thinning to 250 trees per acre at 20 years in Inland Northwest forests.

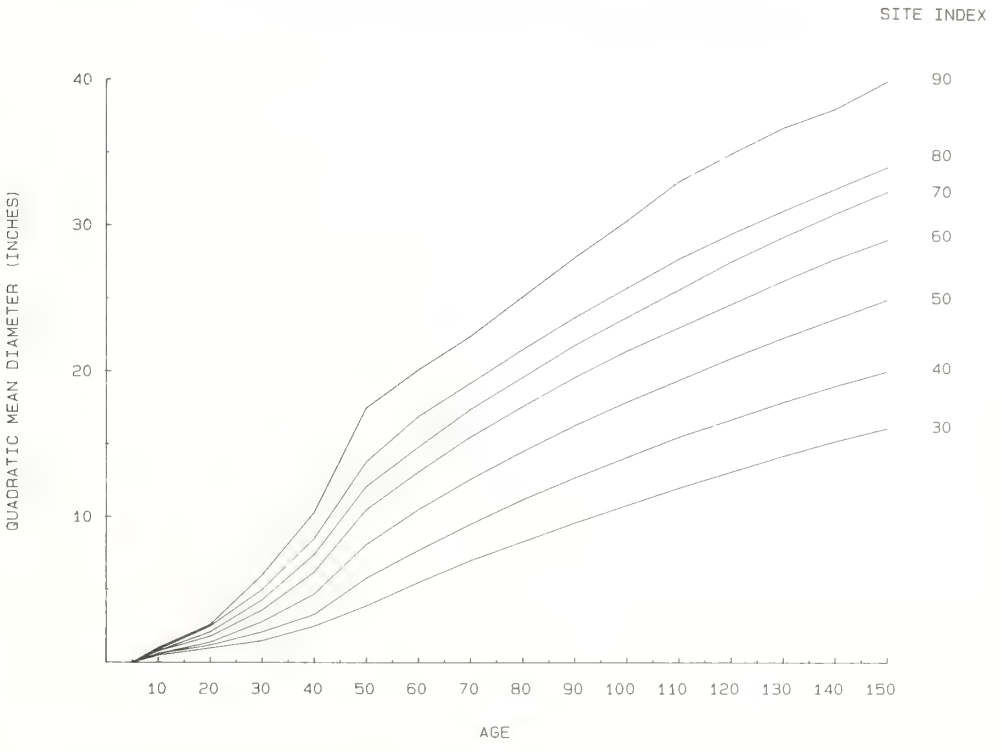


Figure 36—Quadratic mean diameter vs. age for grand fir precommercial thinning to 250 trees per acre at 20 years and commercial thinning from below to 100 trees per acre at 50 years in Inland Northwest forests.

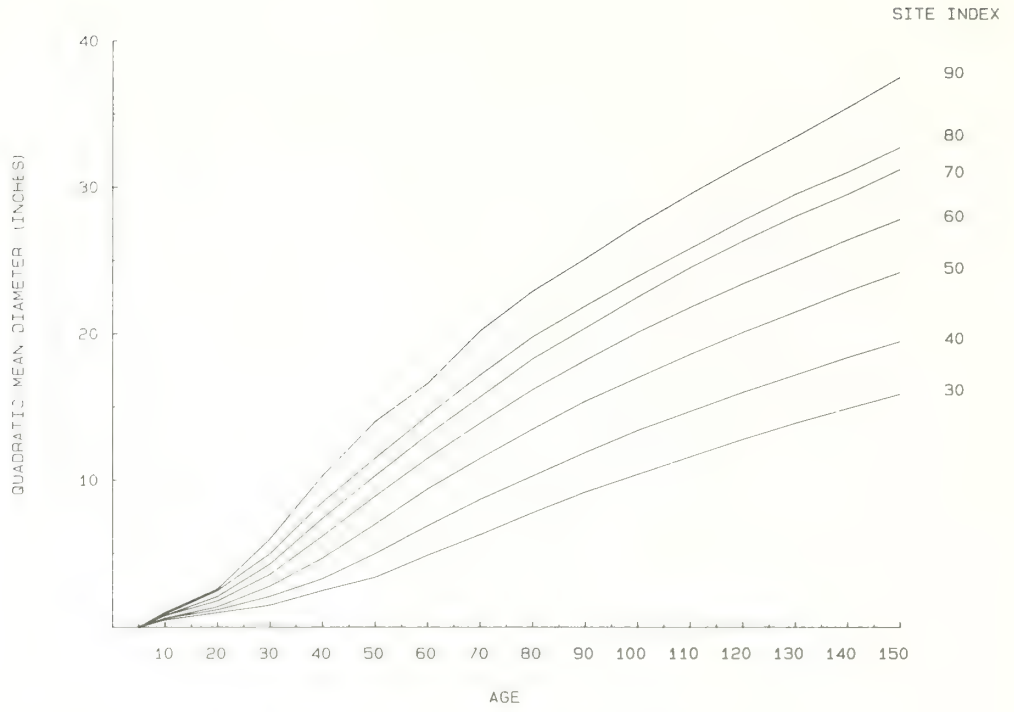


Figure 37—Quadratic mean diameter vs. age for grand fir precommercial thinning to 250 trees per acre at 20 years and commercial thinning to 100 trees per acre at 50 years such that the mean d.b.h. before and after thinning is the same.

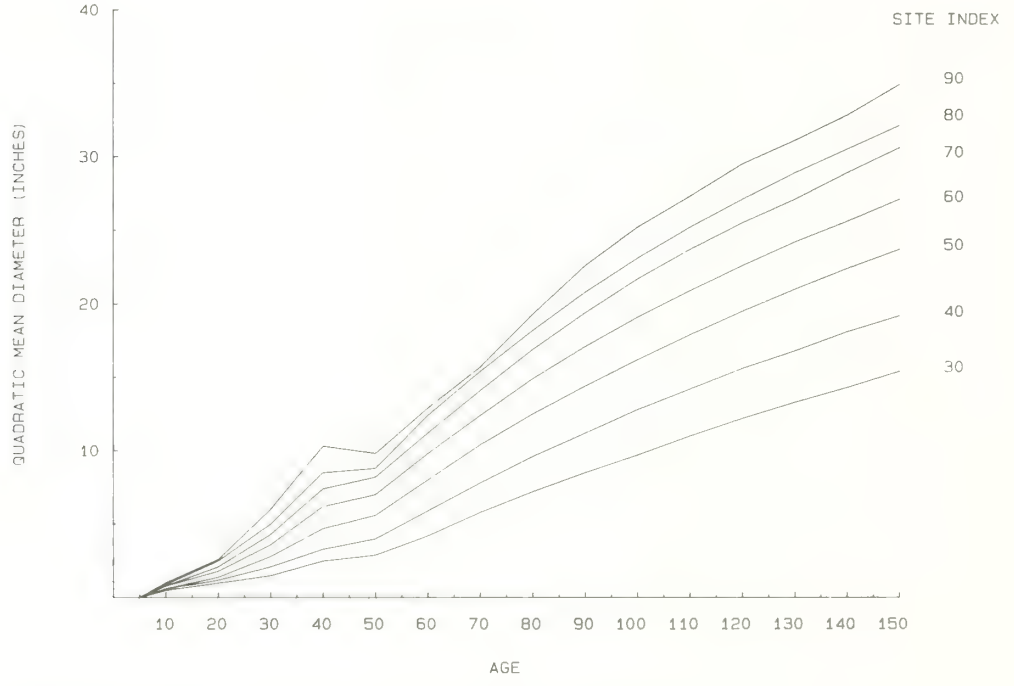


Figure 38—Quadratic mean diameter vs. age for grand fir precommercial thinning to 250 trees per acre at 20 years and commercial thinning from above to 100 trees per acre at 50 years in Inland Northwest forests.

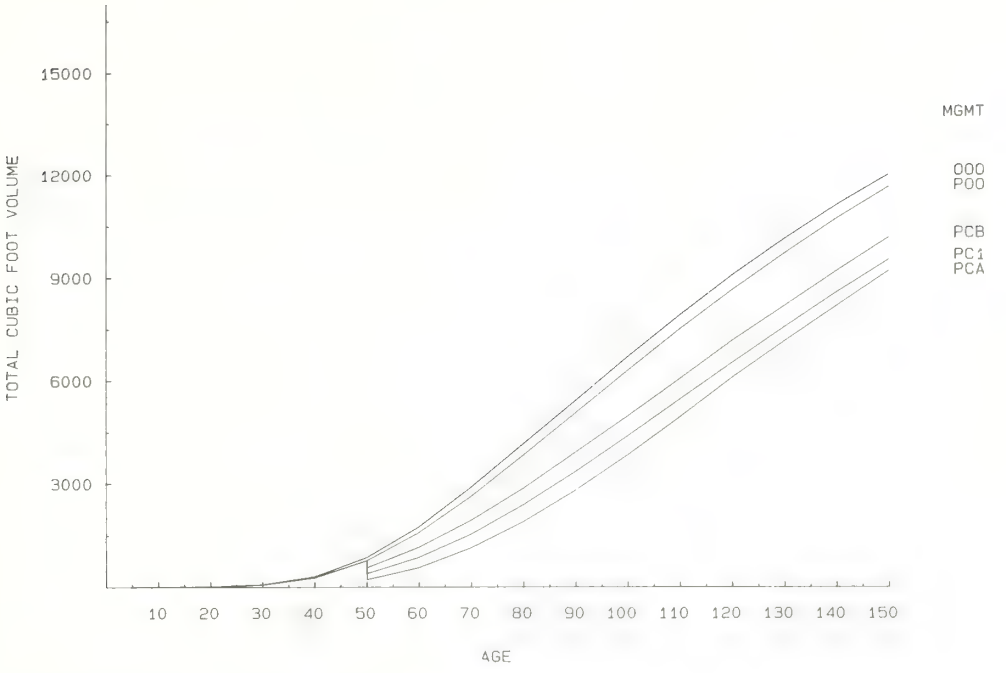


Figure 39—Effect of thinning on standing volume of grand fir plantations (total cubic feet), site index 50.

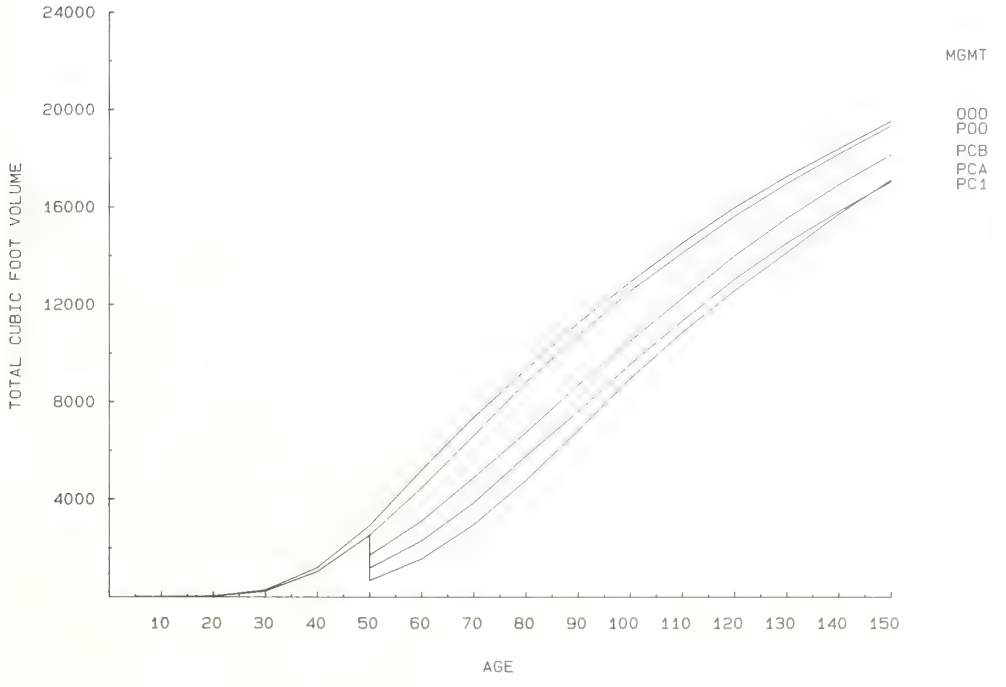


Figure 40—Effect of thinning on standing volume of grand fir plantations (total cubic feet), site index 70.

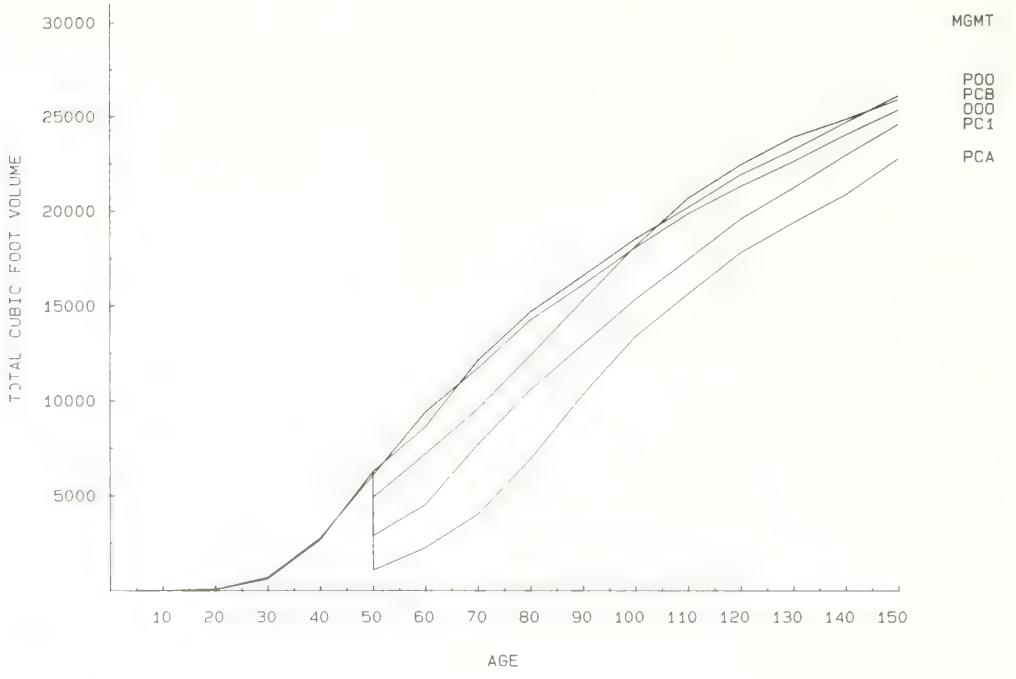


Figure 41—Effect of thinning on standing volume of grand fir plantations (total cubic feet), site index 90.

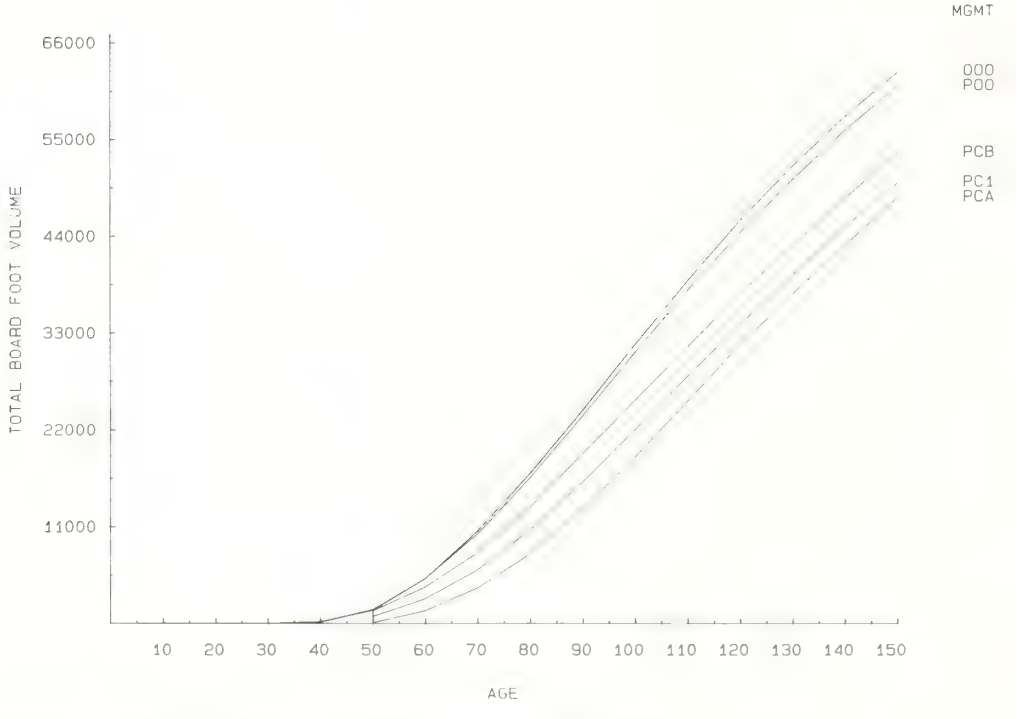


Figure 42—Effect of thinning on standing volume of grand fir plantations (merchantable board feet [Scribner]), site index 50.

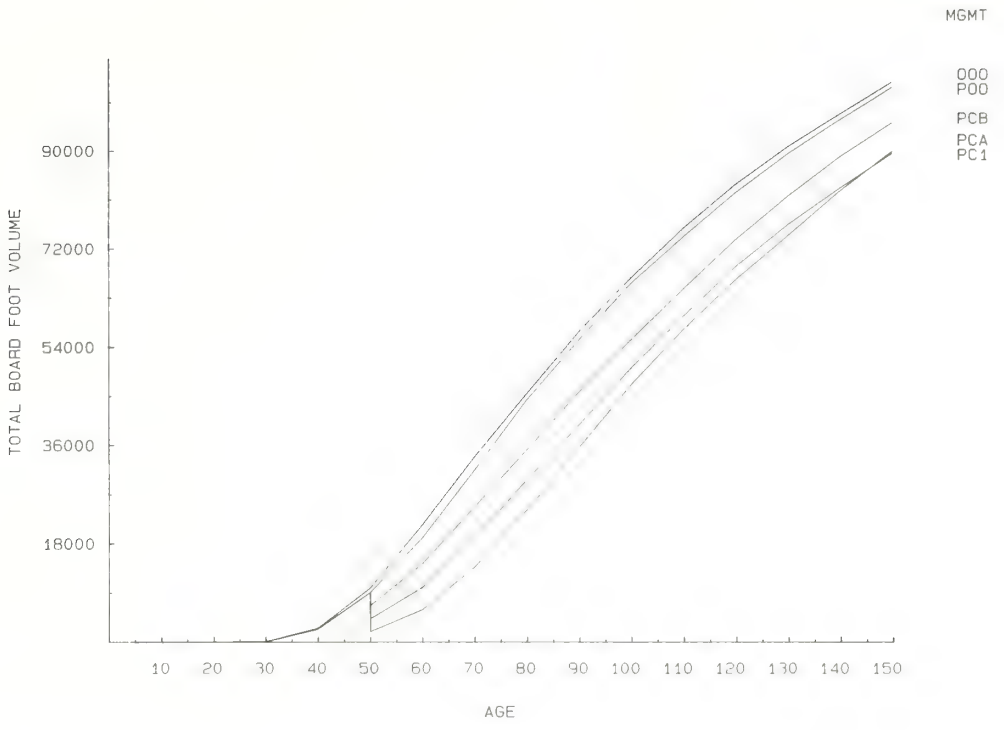


Figure 43—Effect of thinning on standing volume of grand fir plantations (merchantable board feet [Scribner]), site index 70.

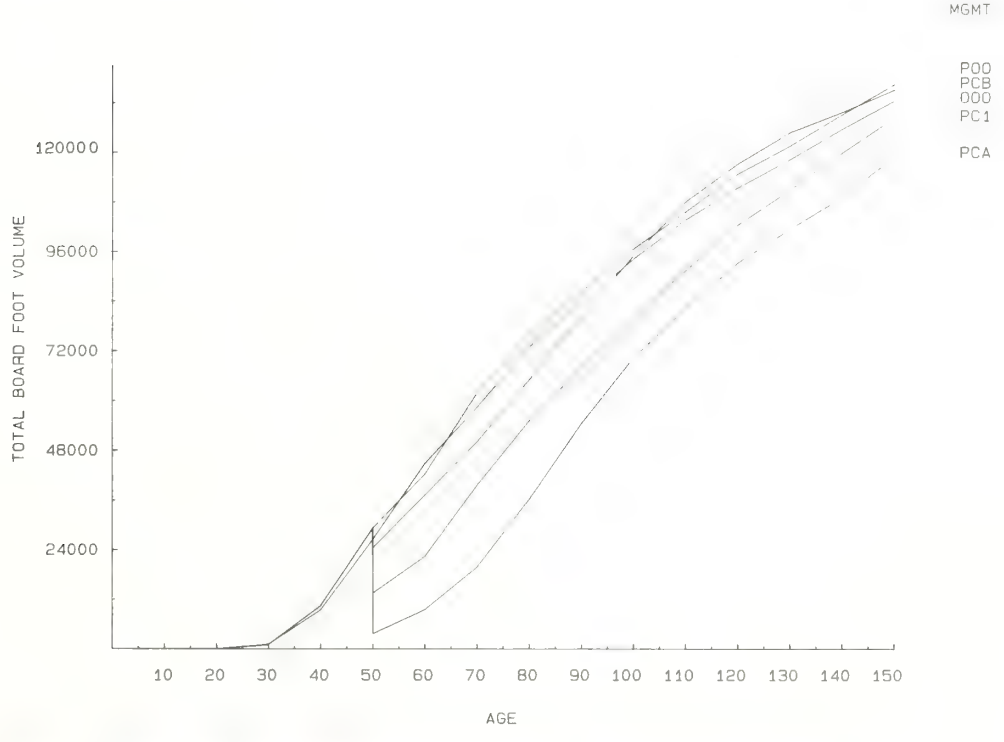


Figure 44—Effect of thinning on standing volume of grand fir plantations (merchantable board feet [Scribner]), site index 90.

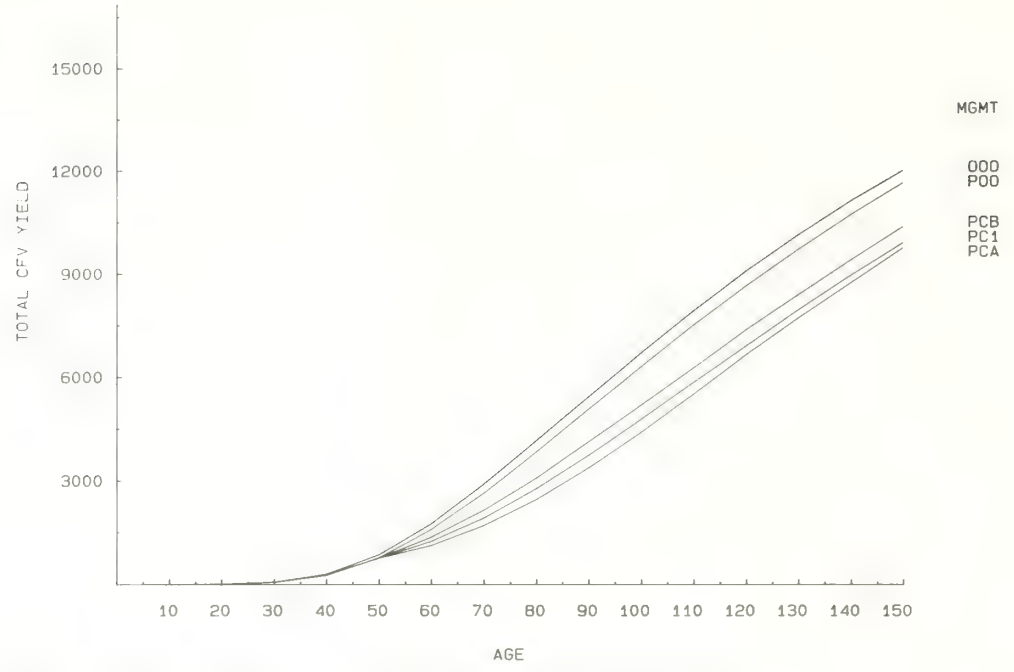


Figure 45—Effect of thinning on total yield of grand fir plantations (total cubic feet), site index 50.

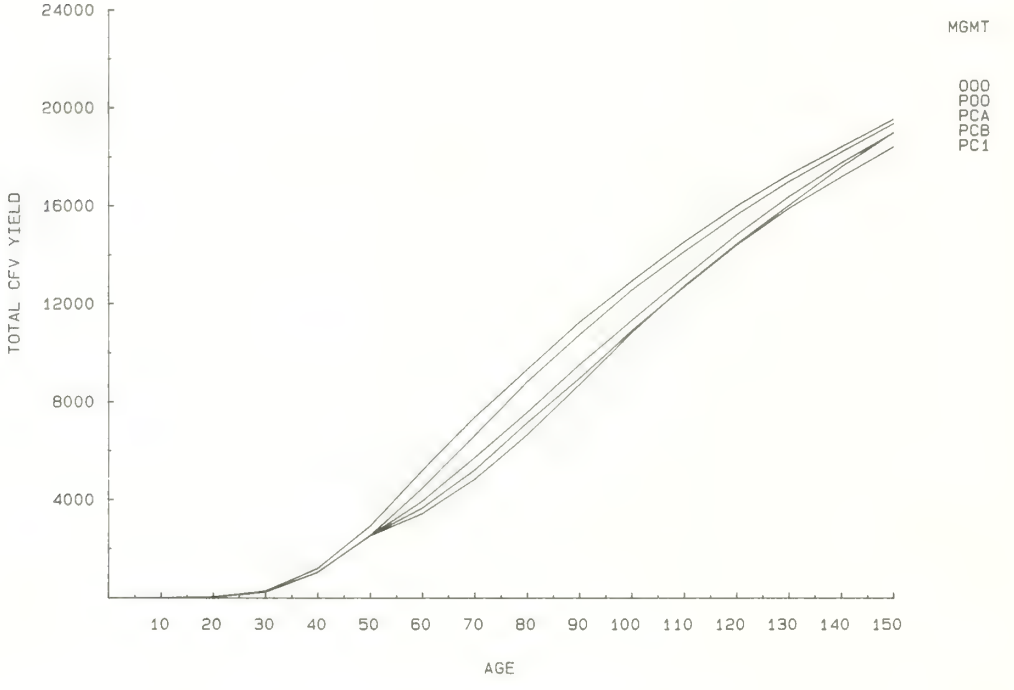


Figure 46—Effect of thinning on total yield of grand fir plantations (total cubic feet), site index 70.

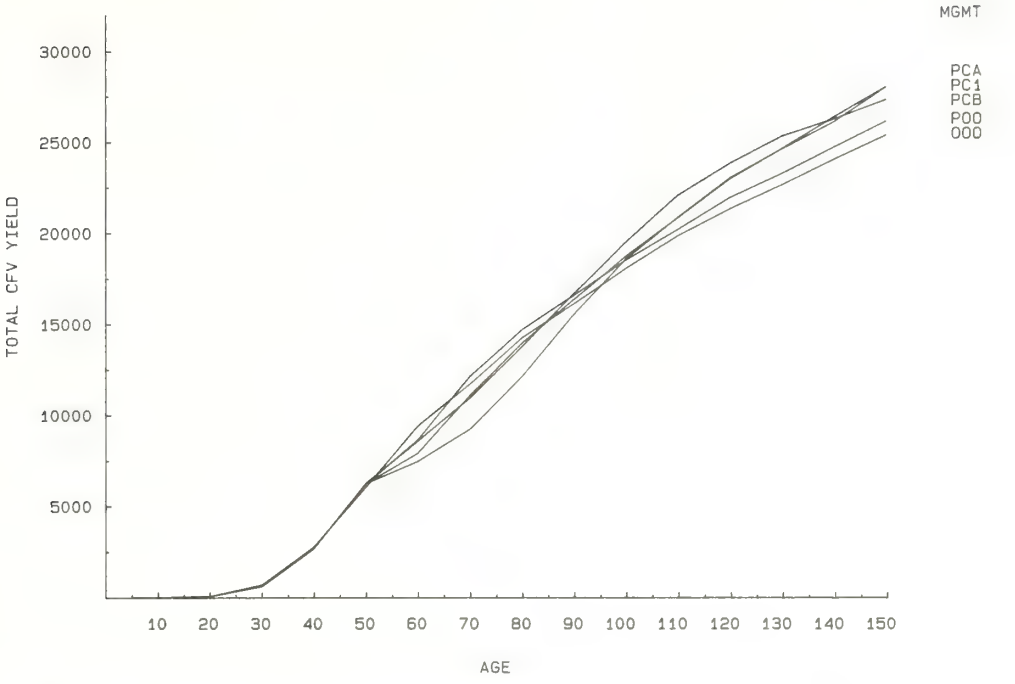


Figure 47—Effect of thinning on total yield of grand fir plantations (total cubic feet), site index 90.

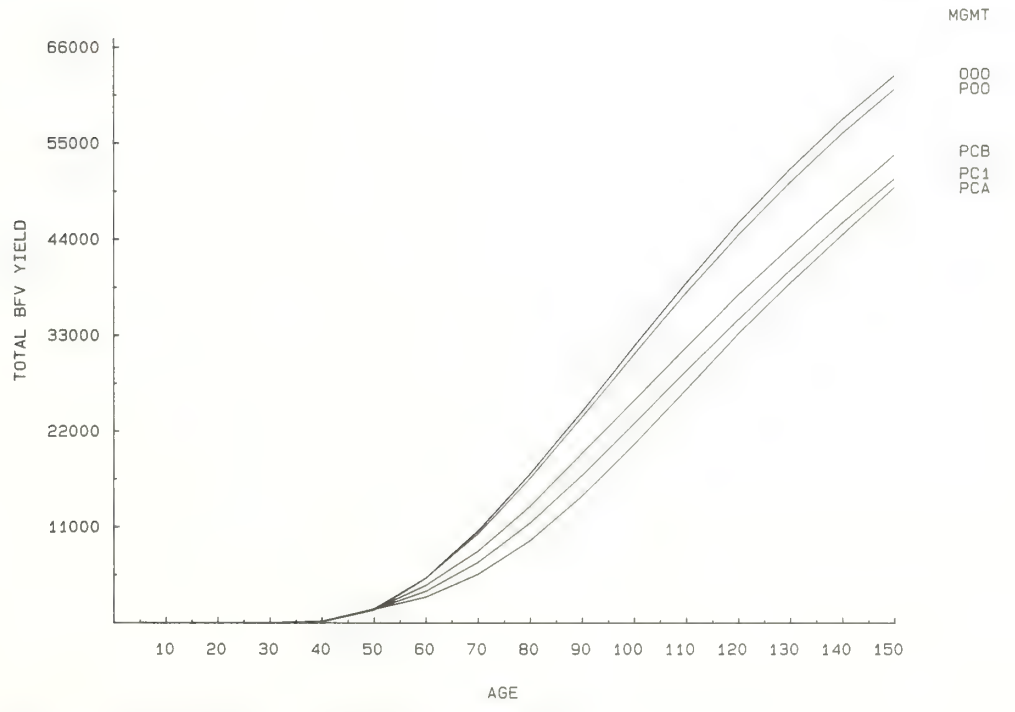


Figure 48—Effect of thinning on total yield of grand fir plantations (merchantable board feet [Scribner]), site index 50.

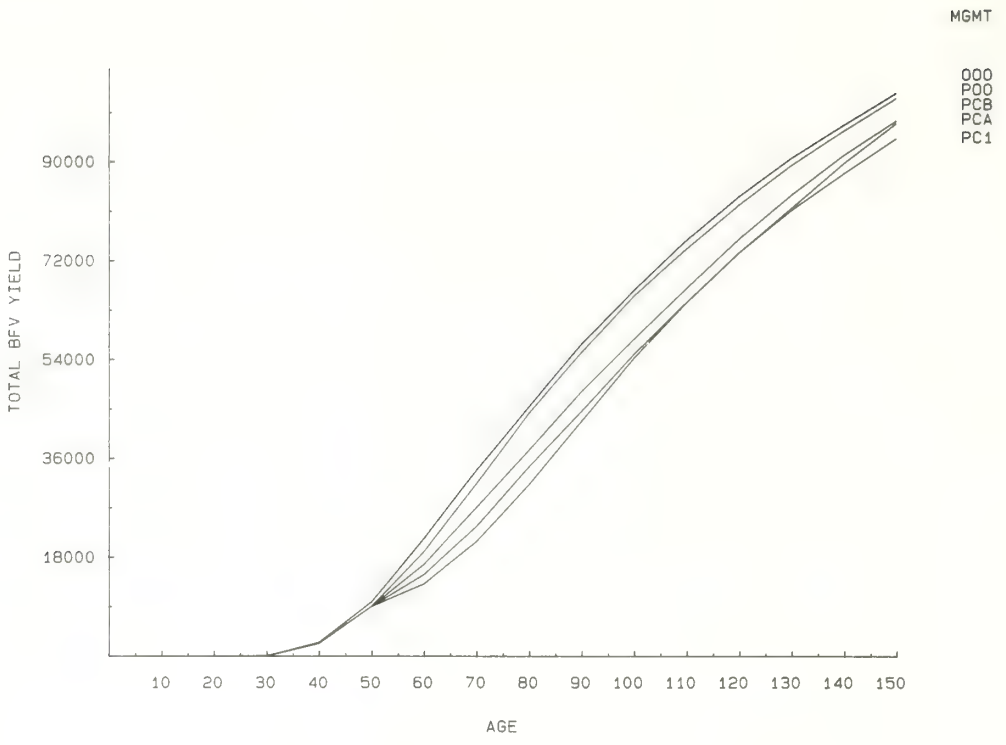


Figure 49—Effect of thinning on total yield of grand fir plantations (merchantable board feet [Scribner]), site index 70.

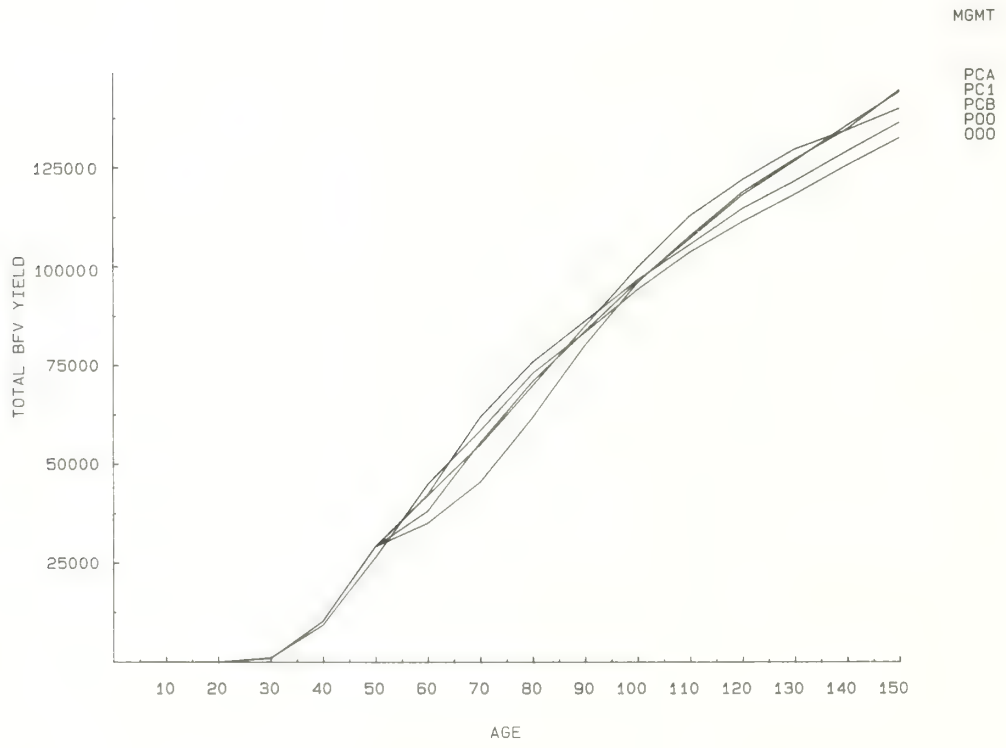


Figure 50—Effect of thinning on total yield of grand fir plantations (merchantable board feet [Scribner]), site index 90.

Western Larch

Yields predicted for western larch plantations in tables 12-16 are the lowest of all the species included in this collection. The lower yields must be attributed to lower levels of stocking because the distribution of site indices (figure 51) is comparable to the distribution for naturally regenerated stands (figure 5) and for Douglas-fir plantations (figure 10). The general shape of the yield curves (figures 52-54) is similar to the corresponding curves for the plantations of the other species. The reduced stocking is attributable to both slower diameter growth (figs. 56 through 60) and higher mortality rates than for Douglas-fir or grand fir. Larch casebearer (*Coleophora laricella*) was a common pest of western larch throughout most of the Inland Empire during the period upon which the Prognosis Model was calibrated. Whether future stands of western larch will continue to be afflicted as much as these data indicate remains to be seen. Effects of thinning regimes on standing volume and total yield are compared in figures 61 through 64 and figures 65 through 68, respectively.

Table 12—Yields of western larch plantations having 500 trees per acre surviving 5 years, no thinning

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	D
				Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3
50	5	500	0	0	0	0	0	0	0	0	1	3	5	0	0	0.0
	10	462	3	0	0	0	0	0	0	1	2	8	10	2	0	0.7
	20	405	19	0	0	0	0	0	0	5	6	16	10	7	0	1.4
	30	349	90	0	0	0	0	0	0	13	15	24	10	18	0	2.7
	40	327	262	4	14	0	0	0	0	28	29	33	10	30	1	3.9
	50	306	553	95	363	0	0	0	0	46	45	41	10	39	3	5.2
	60	287	918	369	1465	0	0	0	0	64	60	48	10	47	4	6.4
	70	268	1343	868	3545	0	0	0	0	81	75	55	10	53	7	7.5
	80	250	1795	1406	5902	0	0	0	0	97	88	61	10	56	11	8.4
	90	233	2248	1945	8334	0	0	0	0	110	98	66	10	56	15	9.3
	100	216	2660	2409	10522	0	0	0	0	120	106	72	10	58	19	10.1
	110	198	3050	2830	12595	0	0	0	0	128	111	77	10	57	22	10.9
	120	182	3395	3194	14491	0	0	0	0	134	115	81	10	57	25	11.6
	130	167	3712	3522	16329	0	0	0	0	138	117	85	10	54	28	12.3
	140	152	3969	3788	17965	0	0	0	0	141	118	89	10	53	31	13.0
	150	139	4189	4015	19451	0	0	0	0	142	118	93	0	0	0	13.7
70	5	500	0	0	0	0	0	0	0	0	1	3	5	2	0	0.0
	10	465	8	0	0	0	0	0	0	3	4	12	10	8	0	1.0
	20	420	83	0	0	0	0	0	0	12	14	25	10	33	0	2.3
	30	372	405	30	116	0	0	0	0	38	38	38	10	66	1	4.3
	40	354	1047	407	1621	0	0	0	0	73	69	49	10	87	5	6.2
	50	329	1855	1300	5387	0	0	0	0	107	98	58	10	97	15	7.7
	60	299	2677	2265	9701	0	0	0	0	134	119	67	10	104	26	9.1
	70	266	3464	3139	13885	0	0	0	0	153	135	75	10	100	35	10.3
	80	235	4111	3842	17486	0	0	0	0	166	142	82	10	99	45	11.4
	90	206	4645	4402	20645	0	0	0	0	173	146	88	10	94	51	12.4
	100	180	5071	4848	23490	0	0	0	0	176	146	93	10	91	56	13.4
	110	158	5421	5214	25957	0	0	0	0	177	145	99	10	89	59	14.4
	120	138	5717	5522	28175	0	0	0	0	177	142	103	10	85	61	15.3
	130	122	5959	5775	30072	0	0	0	0	175	139	108	10	79	62	16.3
	140	108	6129	5955	31427	0	0	0	0	173	136	112	10	77	63	17.2
	150	95	6265	6100	32516	0	0	0	0	169	132	116	0	0	0	18.1
80	5	500	0	0	0	0	0	0	0	0	1	3	5	3	0	0.0
	10	473	14	0	0	0	0	0	0	4	5	14	10	16	0	1.3
	20	437	177	0	0	0	0	0	0	21	22	31	10	66	1	3.0
	30	396	833	205	809	0	0	0	0	63	61	45	10	108	3	5.4
	40	376	1880	1208	4999	0	0	0	0	110	101	58	10	126	14	7.3
	50	341	3000	2502	10719	0	0	0	0	147	132	68	10	133	30	8.9
	60	301	4030	3650	16135	0	0	0	0	172	151	77	10	137	47	10.3
	70	259	4928	4615	21211	0	0	0	0	188	161	85	10	137	61	11.5
	80	221	5685	5410	25918	0	0	0	0	197	165	93	10	130	71	12.8
	90	188	6283	6035	29976	0	0	0	0	200	165	100	10	126	81	14.0
	100	160	6734	6506	33319	0	0	0	0	200	161	106	10	117	84	15.1
	110	137	7066	6855	35826	0	0	0	0	197	157	112	10	108	88	16.3
	120	117	7261	7065	37422	0	0	0	0	192	150	117	10	107	91	17.3
	130	101	7423	7240	38595	0	0	0	0	187	145	122	10	97	85	18.4
	140	88	7544	7372	39451	0	0	0	0	182	139	127	10	92	87	19.5
	150	77	7586	7425	39736	0	0	0	0	176	133	131	0	0	0	20.5

Table 13—Yields of western larch plantations having 500 trees per acre surviving 5 years, precommercial thinning from below to 250 trees per acre at 20 years

Site index	Age	Trees/ acre	Summary statistics: Volume per acre: Total volume	Merchantable volume	Merchantable volume	Removals per acre: Trees/ acre	Total volume	Merchantable volume	Merchantable volume	BA/ acre	CCF	Top height	Growth: PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	1	3	5	0	0	0.0
	10	462	3	0	0	0	0	0	0	1	2	8	10	2	0	0.7
	20	405	19	0	0	155	3	0	0	4	4	16	10	6	0	1.6
	30	221	75	0	0	0	0	0	0	10	11	25	10	14	0	2.9
	40	208	212	7	27	0	0	0	0	21	21	33	10	24	1	4.3
	50	197	444	102	394	0	0	0	0	35	34	41	10	32	2	5.7
	60	187	743	366	1468	0	0	0	0	49	45	48	10	37	3	6.9
	70	178	1088	791	3258	0	0	0	0	62	56	54	10	40	5	8.0
	80	169	1442	1220	5155	0	0	0	0	74	66	61	10	45	8	8.9
	90	159	1810	1638	7078	0	0	0	0	84	75	67	10	45	10	9.9
	100	149	2157	1999	8809	0	0	0	0	93	81	71	10	47	13	10.7
	110	138	2498	2350	10580	0	0	0	0	100	86	76	10	48	16	11.5
	120	129	2827	2682	12336	0	0	0	0	106	91	81	10	46	17	12.3
	130	119	3114	2973	13964	0	0	0	0	111	93	85	10	45	21	13.1
	140	110	3358	3220	15516	0	0	0	0	114	95	89	10	48	23	13.8
	150	102	3603	3468	17134	0	0	0	0	117	96	93	0	0	0	14.5
70	5	500	0	0	0	0	0	0	0	0	1	3	5	2	0	0.0
	10	465	8	0	0	0	0	0	0	3	4	12	10	8	0	1.0
	20	420	83	0	0	170	12	0	0	10	11	25	10	27	0	2.7
	30	233	336	29	113	0	0	0	0	29	29	38	10	53	1	4.8
	40	224	851	391	1566	0	0	0	0	55	52	49	10	73	4	6.7
	50	211	1540	1202	5050	0	0	0	0	82	74	60	10	84	10	8.4
	60	196	2277	2044	8893	0	0	0	0	105	93	69	10	87	17	9.9
	70	179	2971	2774	12439	0	0	0	0	122	106	77	10	89	26	11.2
	80	161	3603	3417	15873	0	0	0	0	135	115	84	10	87	33	12.4
	90	145	4142	3964	19095	0	0	0	0	144	120	90	10	84	39	13.5
	100	129	4595	4423	22036	0	0	0	0	150	122	96	10	84	44	14.6
	110	116	5000	4834	24714	0	0	0	0	154	124	101	10	79	47	15.6
	120	104	5322	5162	26984	0	0	0	0	156	124	106	10	78	51	16.6
	130	93	5598	5443	28934	0	0	0	0	157	123	110	10	76	52	17.6
	140	83	5834	5684	30492	0	0	0	0	157	121	115	10	70	54	18.5
	150	75	5989	5845	31505	0	0	0	0	155	119	119	0	0	0	19.5
80	5	500	0	0	0	0	0	0	0	0	1	3	5	3	0	0.0
	10	473	14	0	0	0	0	0	0	4	5	14	10	16	0	1.3
	20	437	177	0	0	187	29	0	0	16	17	31	10	52	0	3.4
	30	238	664	184	730	0	0	0	0	47	44	46	10	87	2	6.0
	40	229	1514	1111	4642	0	0	0	0	82	74	58	10	108	9	8.1
	50	213	2504	2233	9711	0	0	0	0	113	100	70	10	113	20	9.8
	60	194	3433	3217	14499	0	0	0	0	136	117	79	10	117	34	11.3
	70	173	4266	4061	19071	0	0	0	0	152	128	87	10	117	44	12.7
	80	152	4988	4791	23440	0	0	0	0	162	134	95	10	110	54	14.0
	90	134	5557	5368	27150	0	0	0	0	168	136	102	10	114	63	15.2
	100	117	6066	5885	30686	0	0	0	0	171	136	108	10	104	66	16.4
	110	103	6441	6267	33332	0	0	0	0	172	135	114	10	99	72	17.5
	120	90	6709	6544	35117	0	0	0	0	170	132	120	10	90	76	18.6
	130	79	6855	6699	36088	0	0	0	0	166	127	125	10	89	77	19.7
	140	69	6973	6825	36707	0	0	0	0	162	123	129	10	80	74	20.7
	150	61	7034	6893	36984	0	0	0	0	158	118	133	0	0	0	21.8

Table 14—Yields of western larch plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning from below to 100 trees per acre at 50 years

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	Bd ft		Ft^3	Ft^3	Bd ft	Ft^2		Ft	Yr	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	1	3	5	0	0	0.0
	10	462	3	0	0	0	0	0	0	1	2	8	10	2	0	0.7
	20	405	19	0	0	155	3	0	0	4	4	16	10	8	0	1.6
	30	221	75	0	0	0	0	0	0	10	11	25	10	14	0	2.9
	40	208	212	7	27	0	0	0	0	21	21	33	10	24	1	4.3
	50	197	444	102	394	97	144	1	2	22	21	41	10	21	1	6.4
	60	97	500	316	1279	0	0	0	0	31	28	48	10	25	2	7.6
	70	94	735	619	2592	0	0	0	0	39	35	56	10	28	3	8.8
	80	89	987	892	3839	0	0	0	0	47	42	63	10	28	4	9.8
	90	85	1225	1140	4999	0	0	0	0	54	47	68	10	32	6	10.8
	100	81	1485	1399	6257	0	0	0	0	60	52	73	10	32	7	11.7
	110	76	1732	1646	7547	0	0	0	0	66	56	78	10	33	9	12.6
	120	72	1969	1883	8880	0	0	0	0	71	59	83	10	34	10	13.4
	130	68	2208	2122	10282	0	0	0	0	75	62	87	10	33	12	14.2
	140	63	2422	2335	11616	0	0	0	0	79	64	91	10	32	13	15.1
	150	60	2613	2527	12925	0	0	0	0	81	65	95	0	0	0	15.8
70	5	500	0	0	0	0	0	0	0	0	1	3	5	2	0	0.0
	10	465	8	0	0	0	0	0	0	3	4	12	10	8	0	1.0
	20	420	83	0	0	170	12	0	0	10	11	25	10	27	0	2.7
	30	233	336	29	113	0	0	0	0	29	29	38	10	53	1	4.8
	40	224	851	391	1566	0	0	0	0	55	52	49	10	73	4	6.7
	50	211	1540	1202	5050	111	556	324	1301	50	45	60	10	53	4	9.6
	60	96	1480	1384	6121	0	0	0	0	65	57	69	10	60	8	11.2
	70	89	1997	1897	8715	0	0	0	0	78	66	78	10	64	12	12.7
	80	83	2509	2405	11556	0	0	0	0	90	74	85	10	64	17	14.1
	90	77	2980	2874	14484	0	0	0	0	99	80	92	10	63	21	15.3
	100	71	3403	3296	17102	0	0	0	0	106	84	98	10	63	26	16.6
	110	65	3777	3669	19479	0	0	0	0	111	87	103	10	62	28	17.7
	120	60	4119	4011	21622	0	0	0	0	115	89	108	10	58	30	18.8
	130	55	4400	4292	23317	0	0	0	0	118	90	112	10	58	33	19.9
	140	50	4652	4545	24741	0	0	0	0	120	91	117	10	57	35	20.9
	150	46	4869	4764	25851	0	0	0	0	121	91	121	0	0	0	21.9
80	5	500	0	0	0	0	0	0	0	0	1	3	5	3	0	0.0
	10	473	14	0	0	0	0	0	0	4	5	14	10	16	0	1.3
	20	437	177	0	0	187	29	0	0	16	17	31	10	52	0	3.4
	30	238	664	184	730	0	0	0	0	47	44	46	10	87	2	6.0
	40	229	1514	1111	4642	0	0	0	0	82	74	58	10	108	9	8.1
	50	213	2504	2233	9711	113	912	743	3118	69	60	70	10	70	8	11.2
	60	95	2218	2110	9693	0	0	0	0	84	71	79	10	79	17	12.8
	70	87	2842	2731	13176	0	0	0	0	98	80	87	10	82	21	14.4
	80	80	3449	3335	16987	0	0	0	0	108	87	96	10	85	27	15.8
	90	73	4030	3913	20658	0	0	0	0	118	93	103	10	81	33	17.2
	100	66	4507	4390	23645	0	0	0	0	124	96	109	10	80	40	18.5
	110	60	4912	4795	26092	0	0	0	0	127	97	115	10	77	44	19.7
	120	54	5240	5124	27913	0	0	0	0	129	98	121	10	70	47	20.9
	130	49	5466	5353	29046	0	0	0	0	129	97	125	10	71	51	22.0
	140	44	5662	5552	29865	0	0	0	0	129	96	130	10	65	50	23.1
	150	40	5816	5708	30426	0	0	0	0	128	94	135	0	0	0	24.2

Table 15—Yields of western larch plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning from above to 100 trees per acre at 50 years

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	Bd ft		Ft^3	Ft^3	Bd ft	Ft^2		Ft	Yr	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	1	3	5	0	0	0.0
	10	462	3	0	0	0	0	0	0	1	2	8	10	2	0	0.7
	20	405	19	0	0	155	3	0	0	4	4	16	10	6	0	1.6
	30	221	75	0	0	0	0	0	0	10	11	25	10	14	0	2.9
	40	208	212	7	27	0	0	0	0	21	21	33	10	24	1	4.3
	50	197	444	102	394	97	298	101	394	13	13	35	10	14	1	4.8
	60	93	277	76	295	0	0	0	0	19	18	43	10	20	1	6.2
	70	89	470	286	1162	0	0	0	0	27	25	51	10	25	1	7.5
	80	86	701	581	2441	0	0	0	0	35	32	59	10	26	3	8.7
	90	82	938	847	3651	0	0	0	0	43	38	66	10	30	4	9.7
	100	78	1196	1114	4909	0	0	0	0	49	43	72	10	30	5	10.8
	110	74	1446	1364	6148	0	0	0	0	56	48	77	10	33	7	11.7
	120	70	1707	1625	7531	0	0	0	0	61	52	82	10	31	8	12.6
	130	67	1938	1856	8836	0	0	0	0	66	55	87	10	34	10	13.5
	140	63	2174	2092	10275	0	0	0	0	71	58	91	10	31	11	14.3
	150	59	2378	2296	11543	0	0	0	0	74	60	95	0	0	0	15.1
70	5	500	0	0	0	0	0	0	0	0	1	3	5	2	0	0.0
	10	465	8	0	0	0	0	0	0	3	4	12	10	8	0	1.0
	20	420	83	0	0	170	12	0	0	10	11	25	10	27	0	2.7
	30	233	336	29	113	0	0	0	0	29	29	38	10	53	1	4.8
	40	224	851	391	1566	0	0	0	0	55	52	49	10	73	4	6.7
	50	211	1540	1202	5050	111	1066	952	4051	28	26	53	10	38	4	7.1
	60	92	819	696	2946	0	0	0	0	39	35	64	10	48	4	8.8
	70	87	1255	1160	5089	0	0	0	0	52	46	74	10	54	7	10.5
	80	82	1733	1641	7468	0	0	0	0	64	55	82	10	55	10	12.0
	90	76	2184	2090	9891	0	0	0	0	74	62	89	10	57	14	13.3
	100	71	2621	2525	12458	0	0	0	0	83	68	96	10	62	18	14.6
	110	66	3067	2969	15299	0	0	0	0	91	73	102	10	60	20	15.9
	120	61	3466	3367	17773	0	0	0	0	97	77	108	10	59	24	17.1
	130	56	3812	3713	19922	0	0	0	0	102	79	113	10	59	27	18.3
	140	52	4134	4035	21789	0	0	0	0	106	82	117	10	57	30	19.4
	150	48	4411	4312	23334	0	0	0	0	109	83	122	0	0	0	20.5
90	5	500	0	0	0	0	0	0	0	0	1	3	5	3	0	0.0
	10	473	14	0	0	0	0	0	0	4	5	14	10	16	0	1.3
	20	437	177	0	0	187	29	0	0	16	17	31	10	52	0	3.4
	30	238	664	184	730	0	0	0	0	47	44	46	10	87	2	6.0
	40	229	1514	1111	4642	0	0	0	0	82	74	58	10	108	9	8.1
	50	213	2504	2233	9711	113	1735	1621	7155	37	34	62	10	53	7	8.3
	60	91	1224	1126	4904	0	0	0	0	50	44	74	10	68	8	10.0
	70	84	1826	1729	7836	0	0	0	0	65	56	85	10	73	10	11.9
	80	79	2458	2358	11301	0	0	0	0	79	66	93	10	75	17	13.6
	90	73	3043	2940	14789	0	0	0	0	90	73	102	10	80	23	15.0
	100	67	3609	3504	18314	0	0	0	0	99	79	109	10	76	27	16.5
	110	61	4095	3989	21327	0	0	0	0	106	83	115	10	76	34	17.8
	120	56	4519	4413	23856	0	0	0	0	111	86	121	10	72	36	19.1
	130	51	4878	4773	25844	0	0	0	0	115	87	127	10	71	41	20.3
	140	46	5173	5069	27336	0	0	0	0	117	88	132	10	68	45	21.5
	150	42	5401	5298	28373	0	0	0	0	118	88	136	0	0	0	22.7

Table 16—Yields of western larch plantations having 500 trees per acre surviving 5 years, thinning from below to 250 trees per acre at 20 years, and thinning to 100 trees per acre at 50 years such that the mean d.b.h. before and after thinning is the same

			Summary statistics													
			Volume per acre			Removals per acre							Growth			
Site index	Age	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	Trees/ acre	Total volume	Merchant-able volume	Merchant-able volume	BA/ acre	CCF	Top height	PRD	ACC	MOR/ year	$\bar{D}$
			Ft^3	Ft^3	*Bd ft*		Ft^3	Ft^3	*Bd ft*	Ft^2		*Ft*	*Yr*	Ft^3	Ft^3	
50	5	500	0	0	0	0	0	0	0	0	1	3	5	0	0	0.0
	10	462	3	0	0	0	0	0	0	1	2	8	10	2	0	0.7
	20	405	19	0	0	155	3	0	0	4	4	16	10	6	0	1.6
	30	221	75	0	0	0	0	0	0	10	11	25	10	14	0	2.9
	40	208	212	7	27	0	0	0	0	21	21	33	10	24	1	4.3
	50	197	444	102	394	97	221	52	202	18	17	39	10	18	1	5.7
	60	95	390	198	797	0	0	0	0	25	24	47	10	22	1	7.0
	70	91	597	448	1855	0	0	0	0	33	30	54	10	24	2	8.2
	80	88	819	712	3027	0	0	0	0	40	36	61	10	28	3	9.2
	90	83	1063	975	4248	0	0	0	0	48	42	67	10	29	5	10.2
	100	79	1305	1220	5424	0	0	0	0	54	47	72	10	31	6	11.1
	110	75	1549	1466	6669	0	0	0	0	59	51	78	10	31	7	12.1
	120	71	1783	1700	7939	0	0	0	0	65	54	82	10	32	9	12.9
	130	67	2012	1929	9267	0	0	0	0	69	57	87	10	32	10	13.8
	140	63	2229	2146	10607	0	0	0	0	73	60	91	10	32	12	14.6
	150	59	2434	2351	11912	0	0	0	0	76	62	94	0	0	0	15.4
70	5	500	0	0	0	0	0	0	0	0	1	3	5	2	0	0.0
	10	465	8	0	0	0	0	0	0	3	4	12	10	8	0	1.0
	20	420	83	0	0	170	12	0	0	10	11	25	10	27	0	2.7
	30	233	336	29	113	0	0	0	0	29	29	38	10	53	1	4.8
	40	224	851	391	1566	0	0	0	0	55	52	49	10	73	4	6.7
	50	211	1540	1202	5050	111	815	639	2686	39	35	58	10	46	4	8.4
	60	94	1150	1039	4539	0	0	0	0	52	46	67	10	52	6	10.1
	70	88	1607	1510	6825	0	0	0	0	64	55	76	10	55	9	11.6
	80	82	2063	1966	9274	0	0	0	0	75	63	84	10	56	13	12.9
	90	76	2495	2396	11731	0	0	0	0	84	69	90	10	58	17	14.2
	100	70	2911	2812	14236	0	0	0	0	92	74	96	10	58	20	15.5
	110	65	3294	3193	16690	0	0	0	0	98	78	102	10	58	23	16.6
	120	60	3636	3536	18833	0	0	0	0	103	80	107	10	57	26	17.8
	130	55	3940	3839	20698	0	0	0	0	107	82	111	10	54	29	18.8
	140	51	4196	4096	22219	0	0	0	0	109	83	116	10	55	31	19.9
	150	47	4438	4339	23539	0	0	0	0	111	84	120	0	0	0	20.9
80	5	500	0	0	0	0	0	0	0	0	1	3	5	3	0	0.0
	10	473	14	0	0	0	0	0	0	4	5	14	10	16	0	1.3
	20	437	177	0	0	187	29	0	0	16	17	31	10	52	0	3.4
	30	238	664	184	730	0	0	0	0	47	44	46	10	87	2	6.0
	40	229	1514	1111	4642	0	0	0	0	82	74	58	10	108	9	8.1
	50	213	2504	2233	9711	113	1331	1188	5164	53	47	68	10	63	7	9.8
	60	93	1729	1626	7350	0	0	0	0	67	58	78	10	71	11	11.5
	70	86	2329	2225	10549	0	0	0	0	81	68	87	10	76	16	13.2
	80	79	2929	2822	14040	0	0	0	0	93	76	95	10	77	22	14.7
	90	72	3481	3372	17451	0	0	0	0	102	82	102	10	78	28	16.1
	100	66	3984	3875	20551	0	0	0	0	110	86	109	10	76	33	17.5
	110	60	4415	4305	23153	0	0	0	0	115	89	115	10	73	38	18.8
	120	54	4769	4660	25208	0	0	0	0	118	90	120	10	69	42	20.0
	130	49	5036	4929	26646	0	0	0	0	119	90	125	10	65	46	21.1
	140	44	5233	5128	27559	0	0	0	0	119	89	130	10	62	48	22.3
	150	40	5376	5275	28153	0	0	0	0	118	88	135	0	0	0	23.3

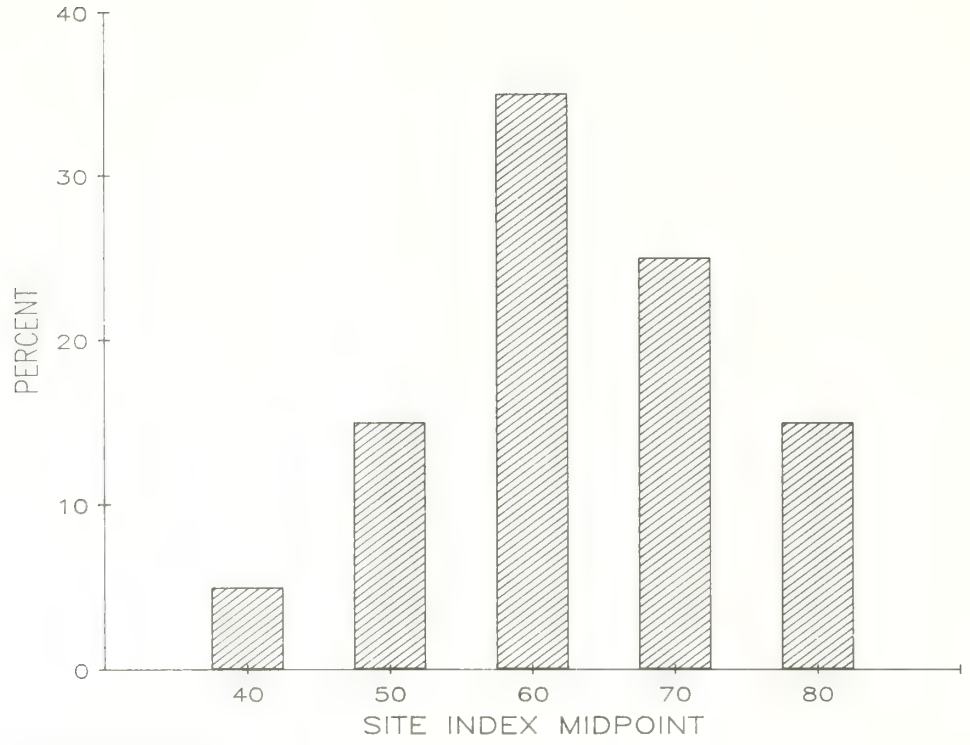


Figure 51—Distribution of western larch plantation site index values for Inland Northwest forests.

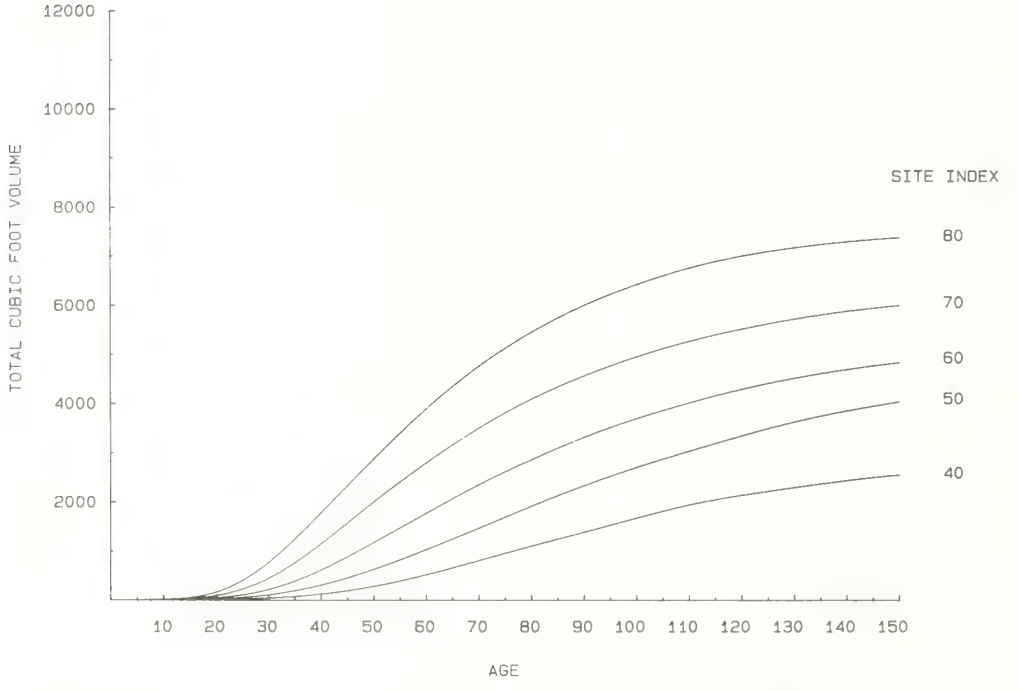


Figure 52—Western larch yield curves for unthinned plantations in Inland Northwest forests (total cubic feet all stems).

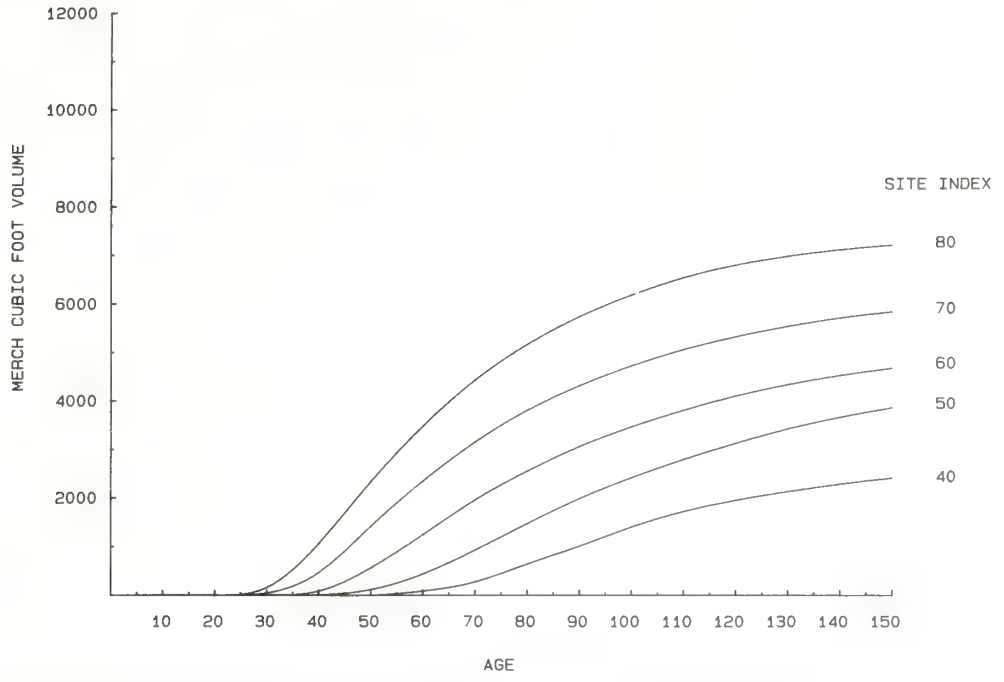


Figure 53—Western larch yield curves for unthinned plantations in Inland Northwest forests (merchantable cubic feet, 4.5-inch top, stems greater than 7 inches d.b.h.).

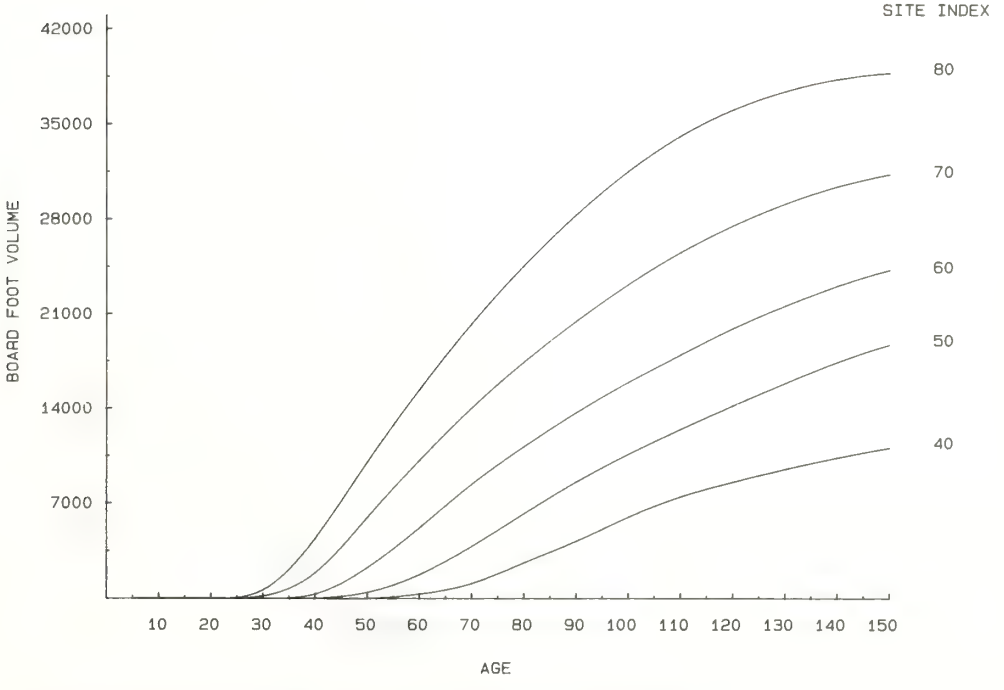


Figure 54—Western larch yield curves for unthinned plantations in Inland Northwest forests (merchantable board feet, 4.5-inch top, stems greater than 7 inches d.b.h.).

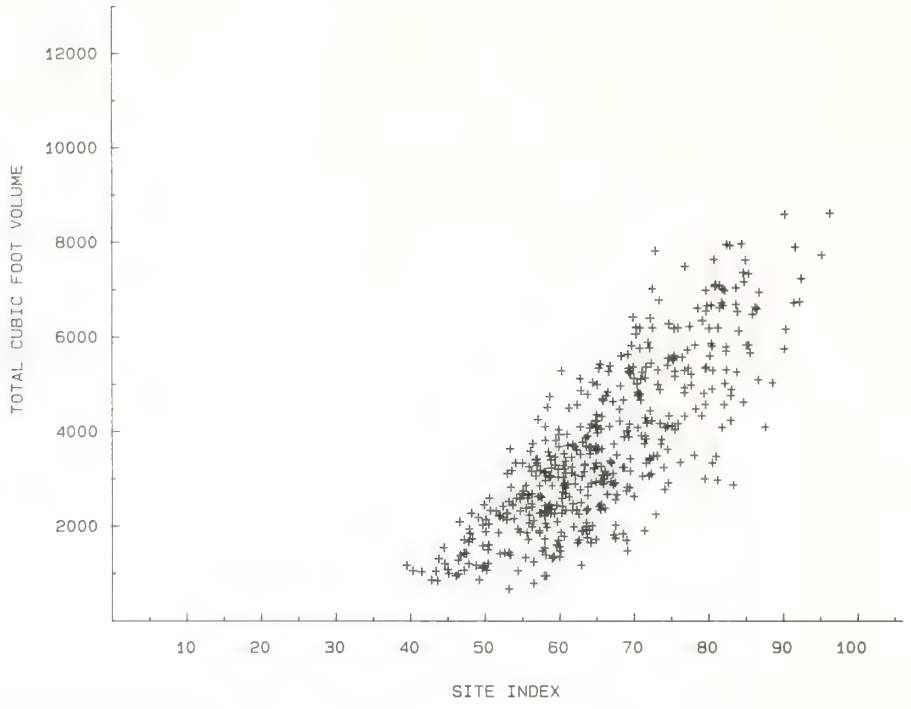


Figure 55—Western larch yield vs. site index at 80 years of age (total cubic feet).

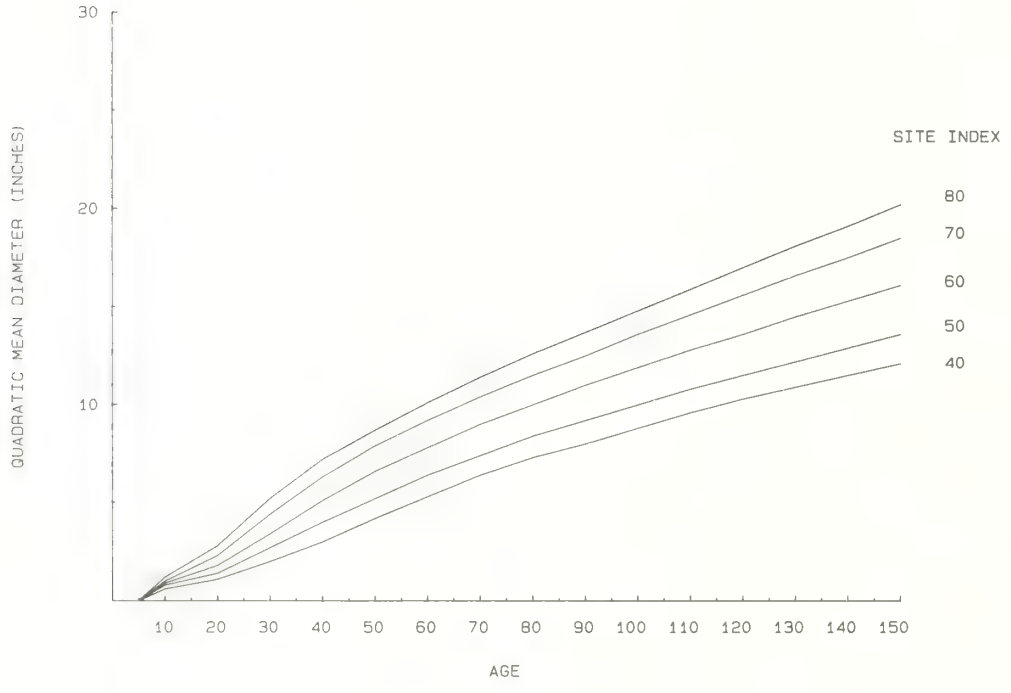


Figure 56—Quadratic mean diameter vs. age for western larch unthinned plantations in Inland Northwest forests.

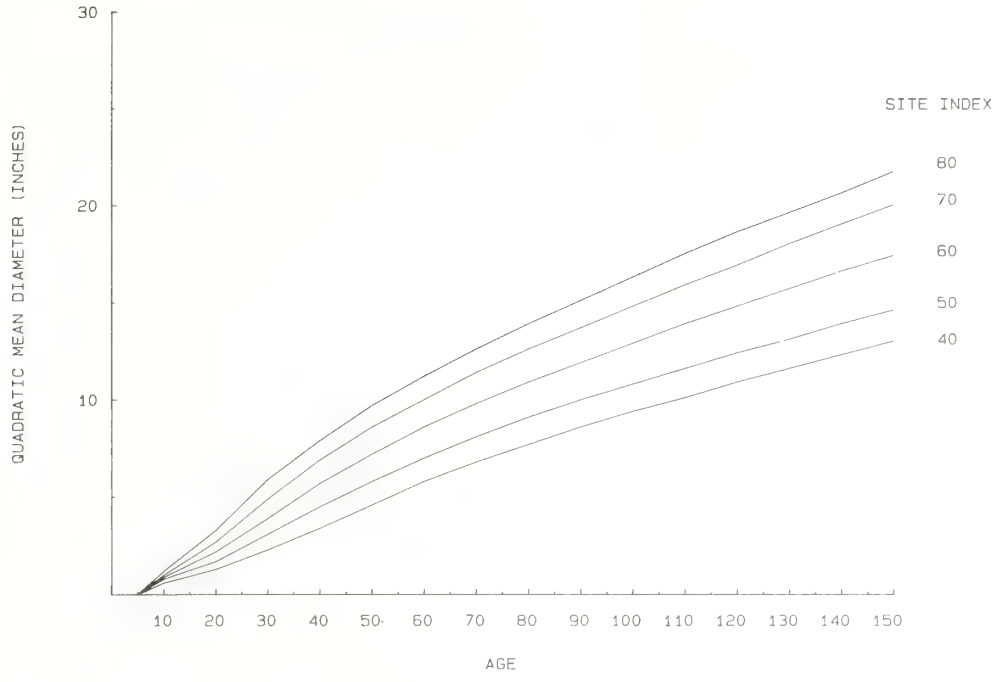


Figure 57—Quadratic mean diameter vs. age for western larch precommercial thinning to 250 trees per acre at 20 years in Inland Northwest forests.

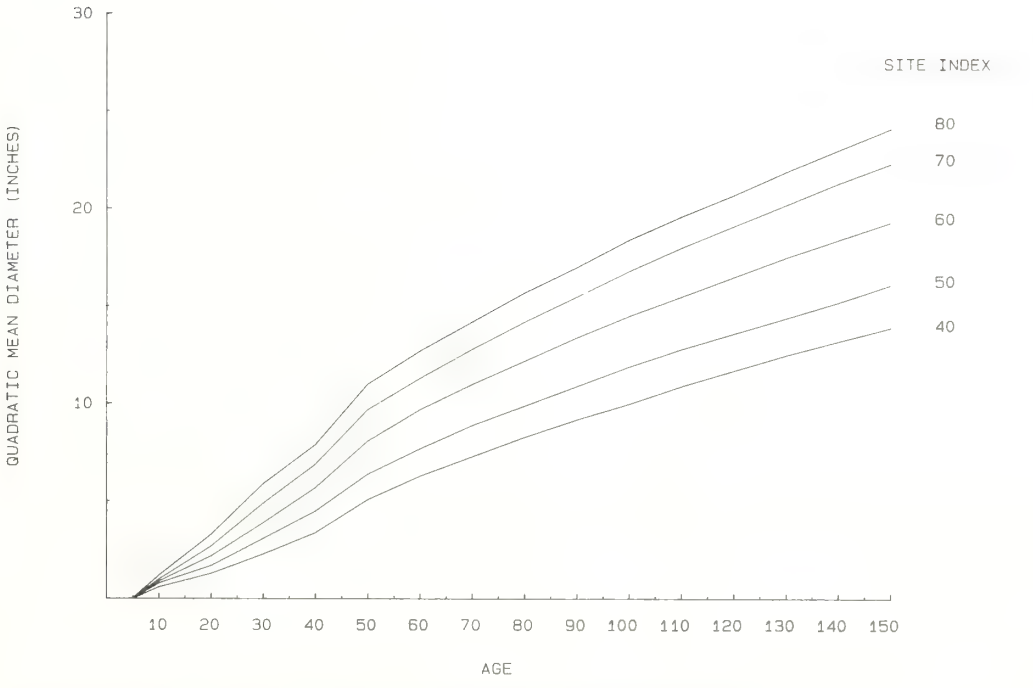


Figure 58—Quadratic mean diameter vs. age for western larch precommercial thinning to 250 trees per acre at 20 years and commercial thinning from below to 100 trees per acre at 50 years in Inland Northwest forests.

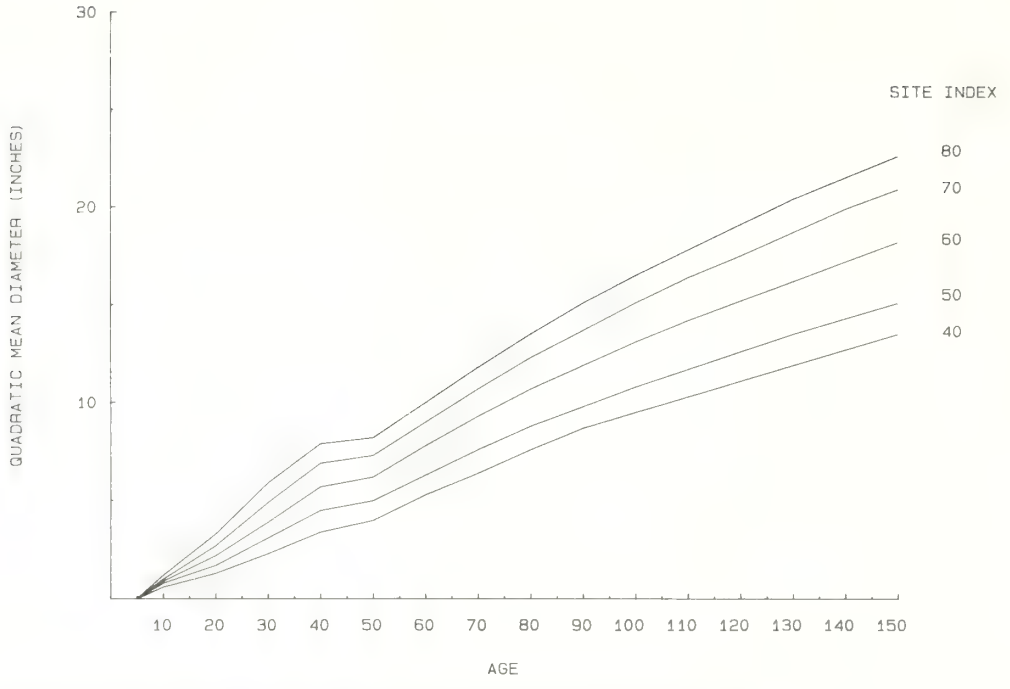


Figure 59—Quadratic mean diameter vs. age for western larch precommercial thinning to 250 trees per acre at 20 years and commercial thinning from above to 100 trees per acre at 50 years in Inland Northwest forests.

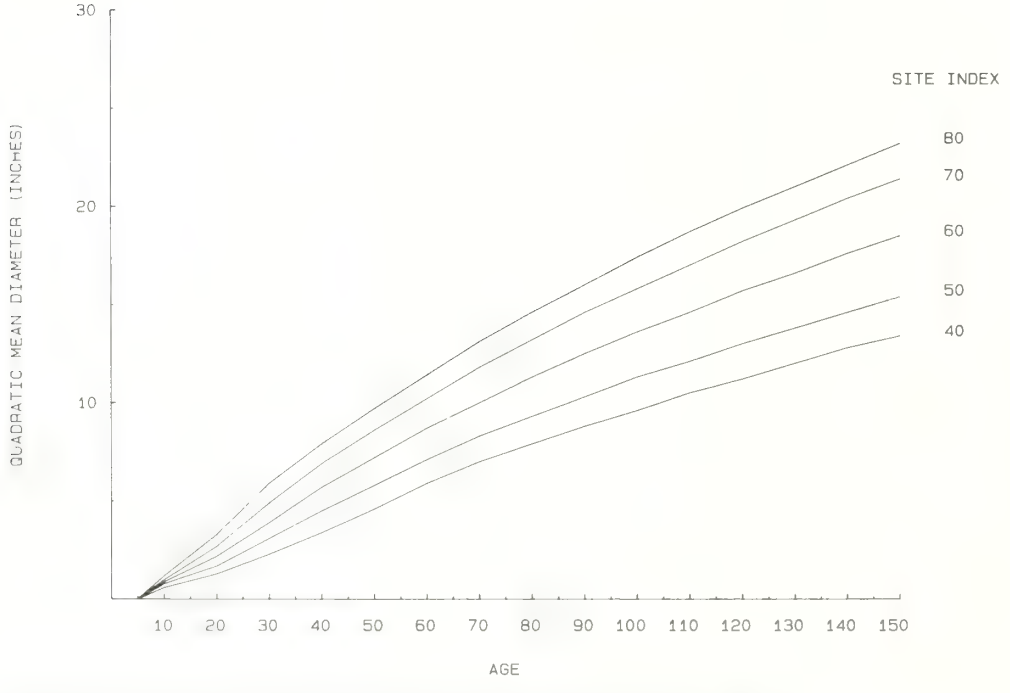


Figure 60—Quadratic mean diameter vs. age for western larch precommercial thinning to 250 trees per acre at 20 years and commercial thinning to 100 trees per acre at 50 years such that the mean d.b.h. before and after thinning is the same.

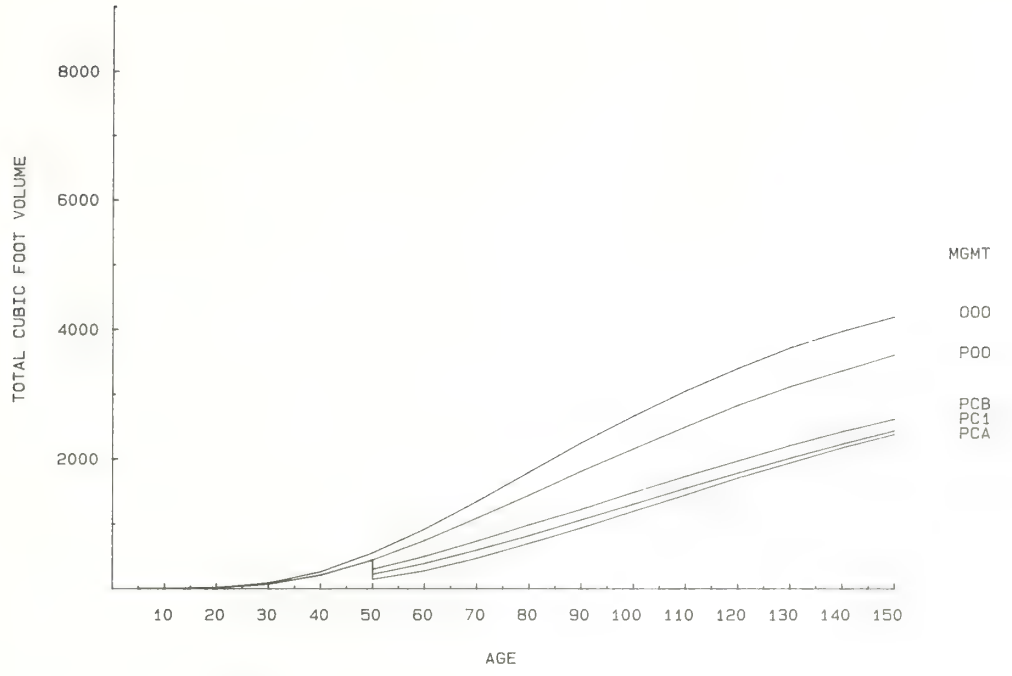


Figure 61—Effect of thinning on standing volume of western larch for Inland Northwest forests (total cubic feet), site index 50.

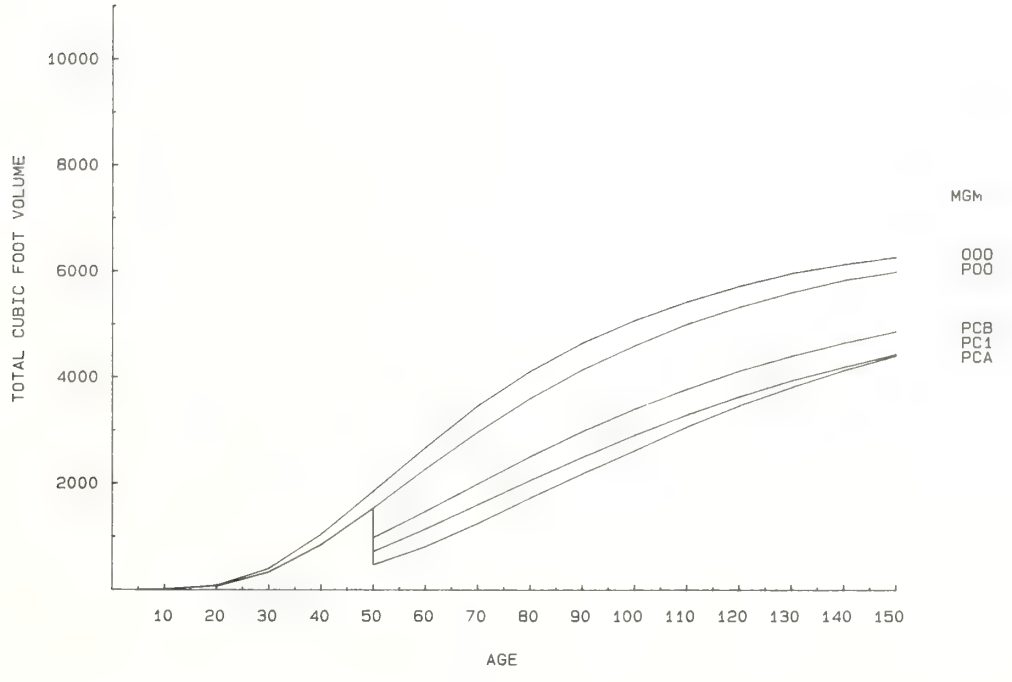


Figure 62—Effect of thinning on standing volume of western larch for Inland Northwest forests (total cubic feet), site index 70.

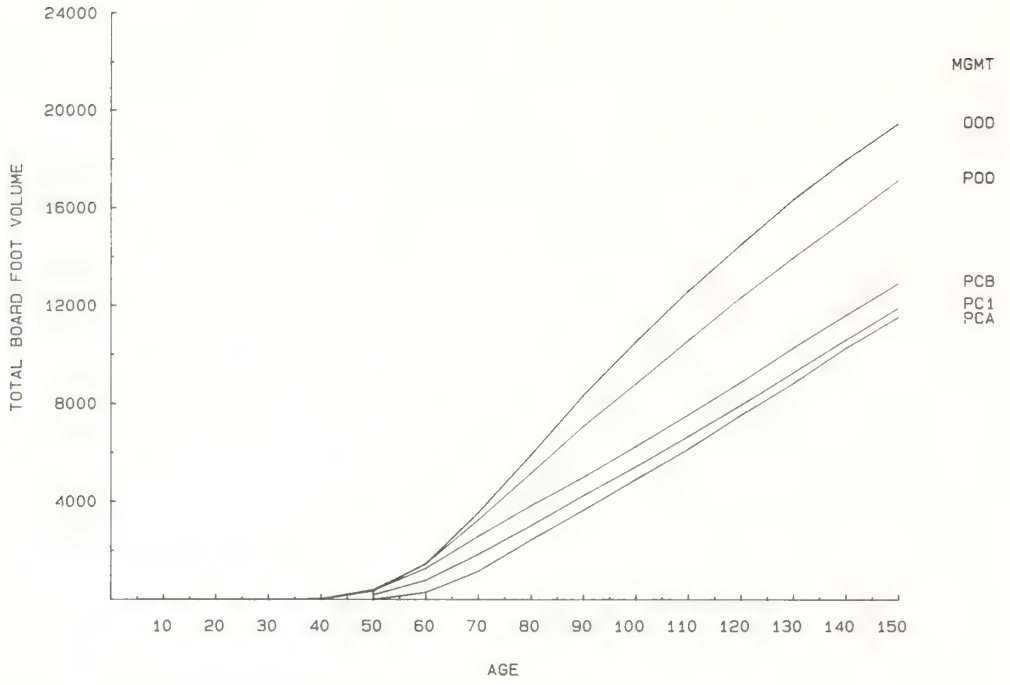


Figure 63—Effect of thinning on standing volume of western larch for Inland Northwest forests (merchantable board feet [Scribner]), site index 50.

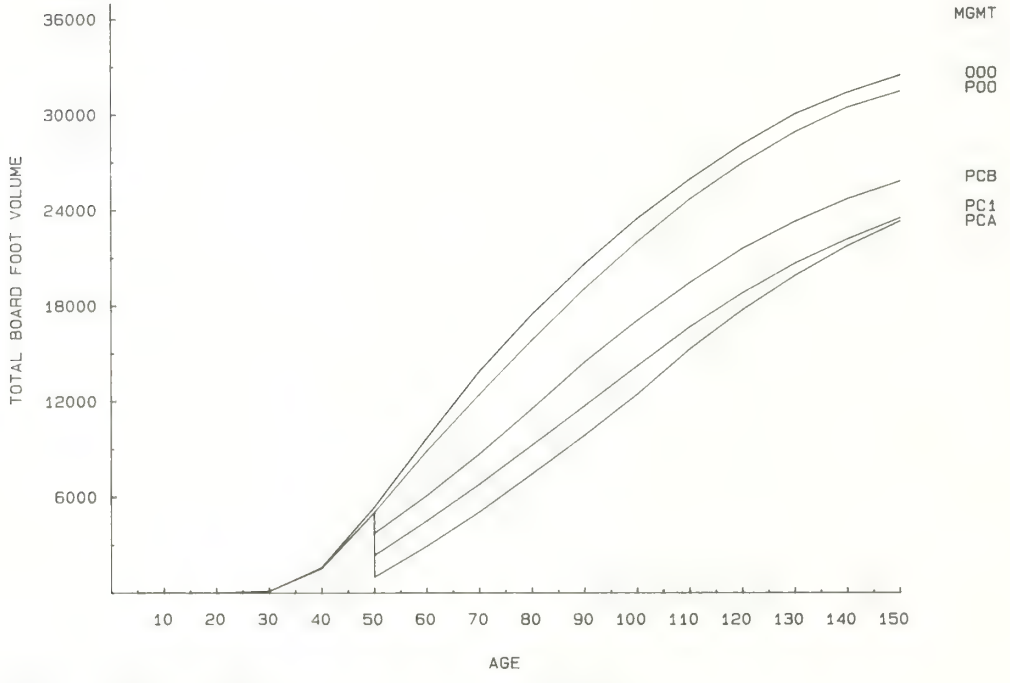


Figure 64—Effect of thinning on standing volume of western larch for Inland Northwest forests (merchantable board feet [Scribner]), site index 70.

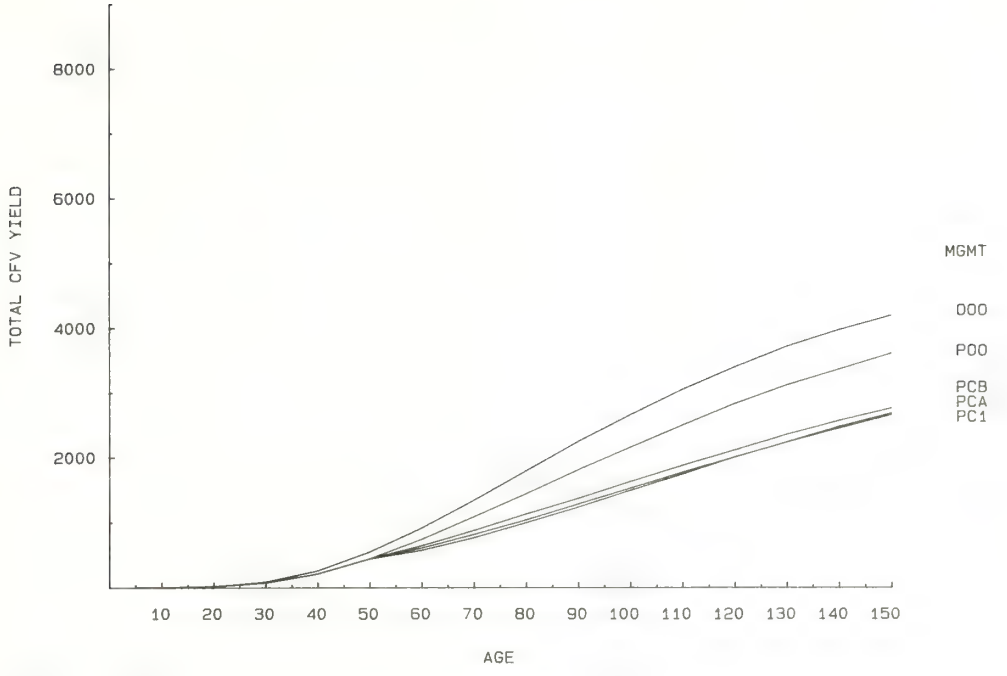


Figure 65—Effect of thinning on total yield of western larch plantations (total cubic feet), site index 50.

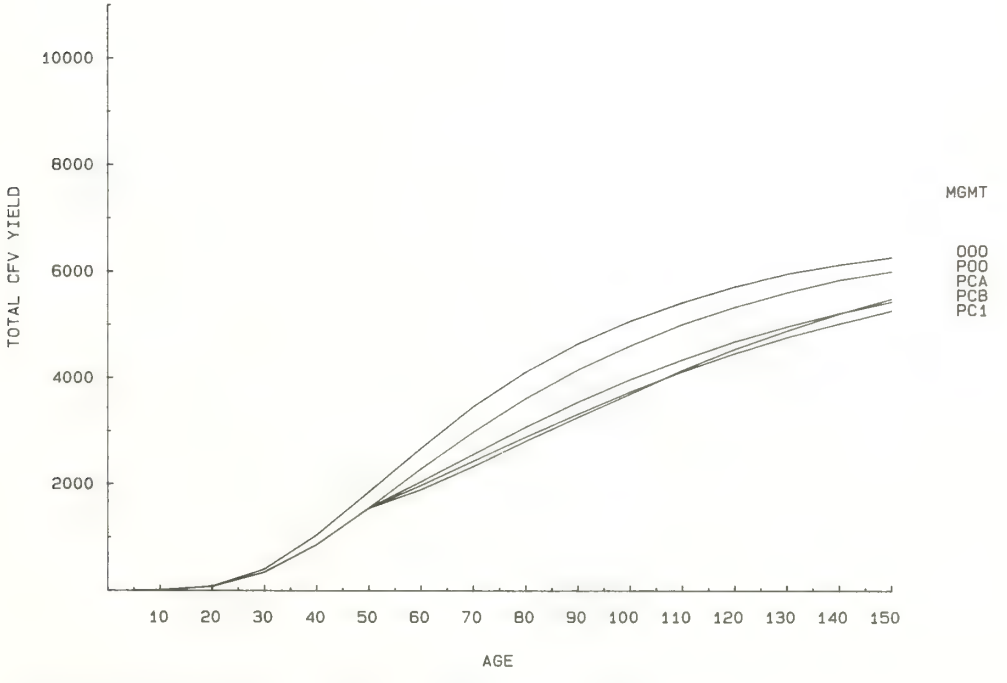


Figure 66—Effect of thinning on total yield of western larch plantations (total cubic feet), site index 70.

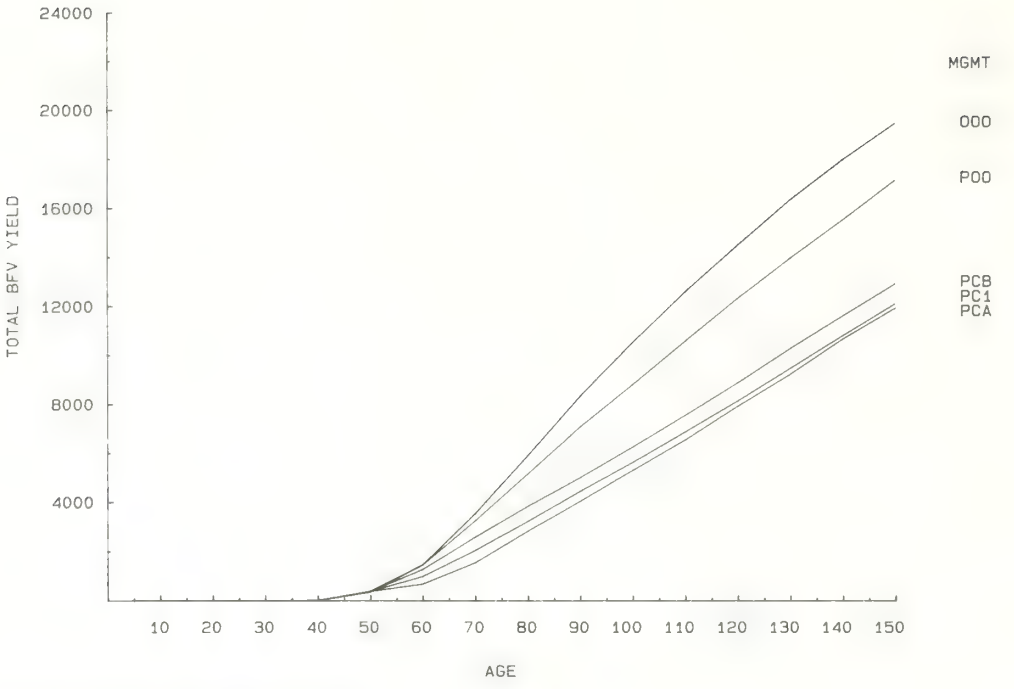


Figure 67—Effect of thinning on total yield of western larch plantations (merchantable board feet [Scribner]), site index 50.

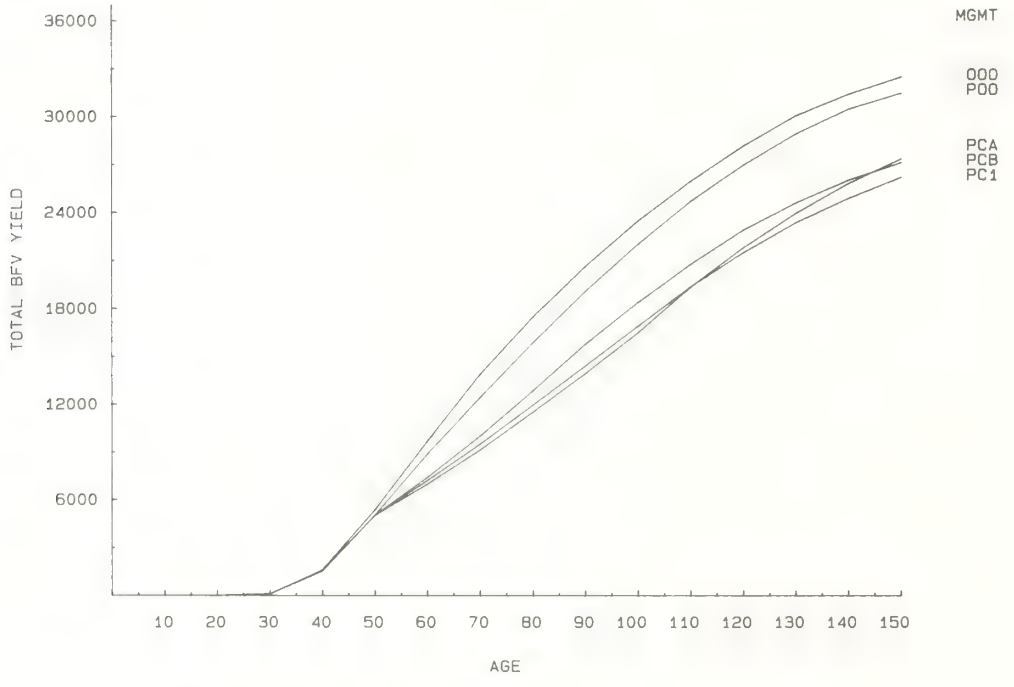


Figure 68—Effect of thinning on total yield of western larch plantations (merchantable board feet [Scribner]), site index 70.

COMPARISON TO RELATED YIELD ESTIMATES

Cochran (1979) has published estimates of net volume yields for natural stands of white (grand) fir and Douglas-fir east of the Cascades in Oregon and Washington. Although his samples were from natural stands, his rigorous screening for uniform spacing, minimal past mortality, and even-aged character of the stand would suggest that the yields he presents might also represent plantations. Furthermore, because his tables are arrayed by breast-high age, effects of the wide variation in early height growth found in natural stands would be reduced. Cochran's site index was defined as the height of the tallest tree on the 1/5-acre plot at 50 years age at breast height. Although his rate of selection of five trees per acre was less than the 20 trees per acre we used, the difference in site index definitions is estimated to be about 3 feet for site indices of about 70 feet. To shift our tables to a breast-high age basis, we estimated years to reach a height of 4.5 feet for plantations from the coefficients in table 13 of Ferguson and others (1986). For combinations of habitat types, elevations, slopes, and aspects that produce site index 70, time from regeneration treatment to 4.5 feet in height was estimated to be 10 years for Douglas-fir trees at +1 standard deviation in the distribution of heights and 16 years for grand fir.

A comparison of the yields reported by Cochran and those reported in this study is presented in figure 69. The curves for Douglas-fir are nearly identical, while for grand fir the Prognosis estimates are consistently higher. The difference in yields of grand fir seem reasonable because we expect grand fir in the Inland Empire to reach higher maximum densities than grand fir growing in eastern Oregon and Washington.

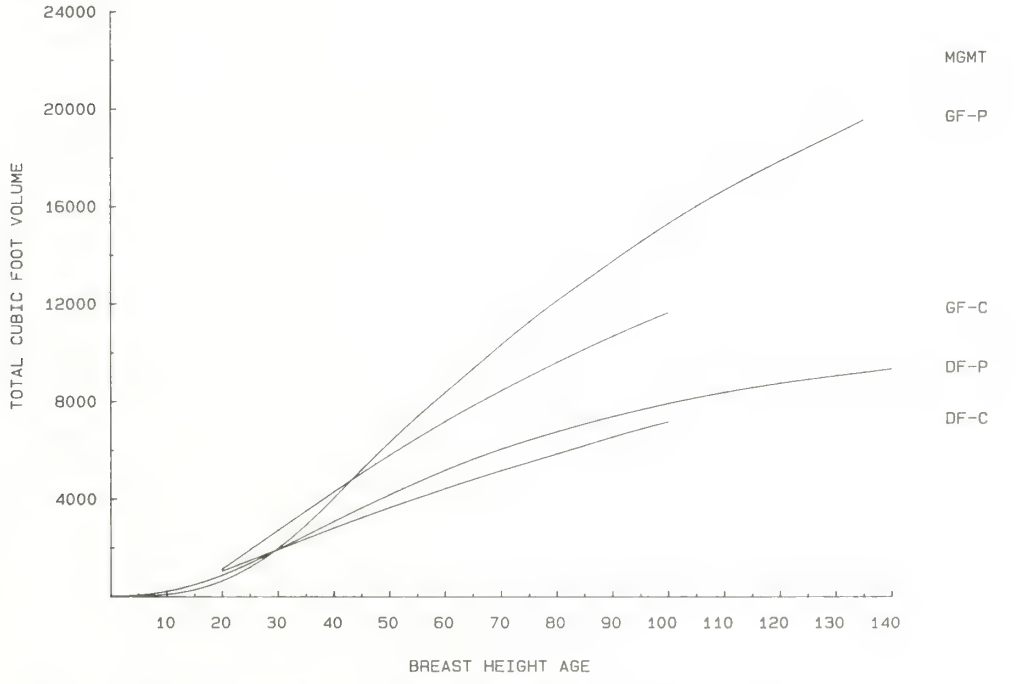


Figure 69—Comparison of Cochran and Prognosis yields for Douglas-fir and grand fir, site index 70. Management codes indicated on this figure are: GF-P = grand fir-Prognosis; GF-C = grand fir-Cochran; DF-P = Douglas-fir-Prognosis; DF-C = Douglas-fir-Cochran.

REFERENCES

Cochran, P. H. 1979. Gross yields for even-aged stands of Douglas-fir and white or grand fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-263. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 17 p.

Daubenmire, R.; Daubenmire, J. 1968. Forest vegetation of eastern Washington and northern Idaho. Tech. Bull. 60. Pullman, WA: Washington Agricultural Experiment Station. 104 p.

Ferguson, D. E.; Stage, A. R.; Boyd, R. J. 1986. Predicting regeneration in the grand fir-cedar-hemlock ecosystem of the Northern Rocky Mountains. For. Sci. Monogr. 26. Washington, DC: Society of American Foresters. 41 p.

Kemp, P. D. 1956. Region 1 volume tables for cruise computations. Northern Region Handbook R1-2430-31. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region.

Stage, A. R. 1987. Progress in yield estimation: a history and prescription. In: Chappel, H. N.; Maguire, D. A., eds. Predicting forest growth and yield: current issues, future prospects. Contrib. 58. Seattle, WA: University of Washington, College of Forest Resources, Institute of Forest Resources: 61-77.

Wykoff, W. R. [In press.] Predicting Basal Area Increment for individual northern Rocky Mountain conifers. Submitted to Forest Science.

Wykoff, W. R.; Crookston, N. L.; Stage, A. R. 1982. User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 112 p.

APPENDIX TABLES: INVENTORY CLASSES USED FOR SIMULATION

Table 17—Class boundaries and corresponding mnemonic codes for Douglas-fir plantations

Variable	Class boundary values	Nominal value for class
Aspect	[1]23-203°	SE
	204-22°	NW
Habitat type	Ponderosa pine series	PSME/PHMA (260)
	Douglas-fir series except PSME/SYAL,PSME/CARU	
	Englemann spruce series	
	Subalpine fir series except ABLA/OPHO,ABLA/CLUN, ABLA/LIBO,ABLA/MEFE, ABLA/LUHI	
	PSME/SYAL	PSME/SYAL (310)
	ABGR/CLUN	ABGR/CLUN (520)
	THPL/CLUN	THPL/CLUN (530)
	TSHE/CLUN	TSHE/CLUN (570)
	ABLA/CLUN	ABLA/CLUN (620)
	ABLA/LIBO	ABLA/LIBO (660)
	ABLA/MEFE	ABLA/MEFE (670)
	TSME/MEFE	TSME/MEFE (680)
	ABLA/LUHI	ABLA/LUHI (830)
National Forest	Bitterroot, Lolo	Bitterroot (3)
	Clearwater	Clearwater (5)
	Coeur d'Alene	Coeur d'Alene (6)
	Colville	Colville (7)
	Flathead	Flathead (10)
	Kaniksu	Kaniksu (13)
	Kootenai	Kootenai (14)
	Nez Perce	Nez Perce (17)
	St. Joe	St. Joe (18)

[1]Aspect is included in class definitions because it is a major source of variation in Regeneration Establishment Model.

Table 18—Class boundaries and corresponding mnemonic codes for grand fir plantations

Variable	Class boundary values	Nominal value for class
Aspect	[1]337-157°	E
	158-336°	W
Habitat type	ABGR/XETE	ABGR/XETE (510)
	ABGR/CLUN	ABGR/CLUN (520)
	THPL/CLUN	THPL/CLUN (530)
	TSHE/CLUN	TSHE/CLUN (570)
	ABLA/CLUN	ABLA/CLUN (620)
	ABLA/MEFE	ABLA/MEFE (670)
	ABLA/XETE	ABLA/XETE (690)
	TSME/XETE	TSME/XETE (710)
National Forest	Bitterroot, Lolo	Bitterroot (3)
	Clearwater	Clearwater (5)
	Coeur d'Alene	Coeur d'Alene (6)
	Colville	Colville (7)
	Flathead	Flathead (10)
	Kaniksu	Kaniksu (13)
	Kootenai	Kootenai (14)
	Nez Perce	Nez Perce (17)
	St. Joe	St. Joe (18)

[1]Aspect is included in class definitions because it is a major source of variation in Regeneration Establishment Model.

Table 19—Class boundaries and corresponding mnemonic codes for western larch plantations

Variable	Class boundary values	Nominal value for class
Aspect	[1]337-157°	E
	158-336°	W
Habitat type	Ponderosa pine series	PSME/PHMA (260)
	Douglas-fir series	
	Subalpine fir series except ABLA/OPHO, ABLA/CLUN, ABLA/LIBO, ABLA/MEFE, ABLA/XETE, ABLA/VAGL, ABLA/VASC	
	Englemann spruce series	PIEN/CLUN (420)
	ABGR/XETE	ABGR/XETE (510)
	ABGR/CLUN	ABGR/CLUN (520)
	THPL/CLUN	THPL/CLUN (530)
	THPL/OPHO	ABLA/OPHO (610)
	TSHE/CLUN	
	ABLA/OPHO	
	ABLA/CLUN	ABLA/CLUN (620)
	ABLA/LIBO	ABLA/LIB0 (660)
	ABLA/MEFE	TSME/MEFE (680)
	TSHE/MEFE	
	ABLA/XETE	ABLA/XETE (690)
	TSME/XETE	TSME/XETE (710)
	ABLA/VASC	ABLA/VASC (730)
National Forest	Colville	Flathead (10)
	Flathead	
	Kootenai	Lolo (16)
	Lolo	
	Bitterroot	Bitterroot (3)
	Clearwater	Clearwater (5)
	Coeur d' Alene	Coeur d' Alene (6)
	Kaniksu	Kaniksu (13)
	Nez Perce	Nez Perce (17)
	St. Joe	St. Joe (18)

[1]Aspect is included in class definitions because it is a major source of variation in Regeneration Establishment Model.

Table 20—Class boundaries and corresponding mnemonic codes for naturally regenerated stands

Variable	Class boundary values	Nominal value for class
Aspect	293-113°	N
	114-292°	S
Habitat type	ABGR/CLUN	ABGR/CLUN (520)
	THPL/CLUN	THPL/CLUN (530)
	TSHE/CLUN	TSHE/CLUN (570)
	ABLA/CLUN	ABLA/CLUN (620)
National Forest	Bitterroot	Bitterroot (3)
	Flathead	
	Lolo	
	Clearwater	Clearwater (5)
	Colville	Colville (7)
	Kaniksu	Kaniksu (13)
	Kootenai	Kootenai (14)
	Nez Perce	Nez Perce (17)

*U.S. GOVERNMENT PRINTING OFFICE: 1988-0-673-039/81006

Stage, Albert R.; Renner, David L.; Chapman, Roger C. 1988. Selected yield tables for plantations and natural stands in Inland Northwest Forests. Res. Pap. INT-394. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 58 p.

Yields arrayed by site index and age have been tabulated for plantations of 500 trees per acre, with five thinning regimes, for Douglas-fir, grand fir, and western larch. Yields were also tabulated for naturally regenerated stands of the grand fir-cedar-hemlock ecosystem of the Inland Empire. All yields were estimated with the Prognosis Model for Stand Development, version 5.2, including the Regeneration Establishment Model.

KEYWORDS: plantation yields, site index, Douglas-fir, grand fir, western larch, natural stand yields, thinning, growth models

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

A 13.78:INT-395

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-395

October 1988

Evaluating Statistical Techniques for Predicting and Interpreting FORPLAN Results

James F. C. Hyde III
J. Greg Jones
Mary L. Meacham

UNIVERSITY OF NEVADA RENO

$$PNV = b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_n X_n$$

Evaluating Statistical Techniques for Predicting and Interpreting FORPLAN Results

James F. C. Hyde III
J. Greg Jones
Mary L. Meacham

INTRODUCTION

Many management objectives cannot be adequately reflected in terms of monetary value in the objective function in the linear programming formulations developed in FORPLAN. Examples include maintaining local economic stability and providing nonmarket benefits such as recreation or wildlife for which there are no suitable valuation methods. Objectives such as these are generally entered in the form of constraints. These management objectives, hereafter called constraints, can be expensive, both in terms of increased direct operating costs (Kemper and Davis 1976) and in outputs forgone (Bell and Randall 1982; Fight and others 1978). Identifying the appropriate constraints and levels thereof involves weighing the benefits of including the constraints against their costs. The approach recommended by the Secretary's Office, U.S. Department of Agriculture (MacCleery 1982) and suggested by numerous authors (for example, Fight and Randall 1980; Hughes 1965; Jones and others 1978) is to estimate the cost of a constraint in terms of the quantifiable outputs impacted, measured in terms of reduction in present net value or some analogous measure. A subjective judgment of the value of the constraint (because its value cannot be quantified) is then compared to the quantified cost to evaluate the constraint. Obviously, the constraint is desirable if its benefits are perceived to exceed its cost.

There are two common approaches for estimating the cost of constraints in linear programming models. One is the "shadow price" that is calculated for each constraint in the process of solving the linear program. The shadow price for a constraint measures the change in the objective function associated with changing that constraint by one unit, all else remaining constant. This cost, however, holds only over very small changes in the constraint. If the cost of a larger increment in a constraint is desired, the second approach for estimating cost is used. In this approach the model is solved twice, once with the constraint present at the current level and once with it set to a substantially different level, all else held constant. The cost of the constraint is the difference in the objective function values between the two solutions.

If the effects of a constraint on the objective function were independent of the other constraints imposed, the cost would only have to be calculated once for each constraint, since it would be constant over all situations. Experience has shown, however, that the cost of a constraint is seldom independent, but rather depends on the level and combination of other constraints imposed in the model. As a result, a large number of FORPLAN solutions would be required to identify the cost of a number of constraints over a variety of situations. FORPLAN solutions are expensive (often in the hundreds of dollars), yet the cost of constraints is needed to provide reasonable assurance that appropriate constraints are imposed at appropriate levels for each management alternative identified in forest planning. A less expensive method for estimating the cost of management constraints would be useful.

Multiple regression analysis could provide a third method for evaluating these costs. It involves applying multiple regression analysis to the results generated by FORPLAN. Equations could be developed that relate a dependent variable measuring present net value (or other objective functions), to independent variables measuring the extent to which constraints are imposed in FORPLAN solutions (acres of partial retention visual management, animal unit months of big game winter range, and so forth).

Such regression equations could serve two separate but related purposes. First, they could be used to predict values for the dependent variable given values of the independent constraint variables in the equation. Second, such regression equations could be used for explanatory purposes. In this use, the regression coefficients would measure the relationship exhibited between the dependent and independent variables.

If this application of regression proved successful, it would be useful in a number of ways during the latter stages of planning. For example, such equations could be used as an aid in "fine-tuning" management alternatives in forest planning. In some instances it may be desirable to relax certain constraints if such a change would save a large incremental cost. In other cases, it may be found that additional constraints could be imposed with little or no added cost. In addition, the procedure could be used to predict the cost of changes in alternatives proposed by the public in the review process of forest planning. This would aid Forest Service planners and decision makers in evaluating such suggestions and could provide some documentation underlying the ultimate decisions.

This paper reports the results of testing two approaches in which multiple regression techniques are used to fit present net value as a function of constraint variables. In one approach, called the ordinary least squares (OLS) approach, the constraint variables themselves are the independent variables in the regression model. In the second approach, principal component analysis with

regression (PCAR), principal components are computed from the original set of constraint variables. Then, multiple regression is used to fit present net value as a function of these principal components.

METHODS

The experiment was conducted using planning data from three National Forests in the Northern Region (Region 1): the Beaverhead, the Gallatin, and the Lolo. These Forests were selected because they were among those forests far enough along in the planning process to provide suitable data at the time the study began. Separate regression equations were developed for each Forest.

The FORPLAN solutions made in the forest planning process on these Forests served as the data base. Solutions were generated in two stages of planning. The first stage, called the analysis of the management situation, identified the range of outputs possible on the Forest, thereby defining the decision space for forest planning. Solutions generated in this stage vary substantially in terms of constraints imposed. In the second stage, management alternatives are developed. Generally, at least several solutions are made in the development of each management alternative, with a total of 20 to 40 solutions produced by this stage.

Our study began with approximately 33 solutions per Forest. It was necessary, however, to discard some of the FORPLAN solutions in order to maintain a consistent data base within each Forest. The solutions discarded include solutions with objective functions other than PNV and solutions that had different cost or price data, or a different base year for expressing constant dollars. The resulting data base consisted of 26 solutions for the Beaverhead National Forest, 25 solutions for the Gallatin National Forest, and 23 solutions for the Lolo National Forest.

The observed values for the dependent variable were the PNV objective function values (measured in thousands of dollars) obtained in the FORPLAN solutions. The independent variables measured the constraints imposed. In each Forest more than 100 such variables were developed. Some constraints were quantified as continuous variables. Examples include constraints placed on the volume of timber to be harvested in a particular decade, the acres of land to be allocated to specified uses such as wilderness and big game winter range, and acres to be managed with a high visual quality objective. For these, the right-hand-side value became the observed value. Other constraints, such as the nondeclining yield constraints, were quantified as dummy variables, where a value of 1 indicated the presence of the constraint at a given level and 0 the absence.

Many constraints measured as continuous variables were missing in at least several solutions. This posed no problem for lower limit constraints; for these variables a value of 0 was used when a constraint was not present (a lower limit of 0 is in fact equivalent to no constraint if the coefficients in the constraint are positive). A problem, however, arose in coding upper limit and equality constraints, which were quantified as continuous variables. Missing observations in equality and upper limit constraints could not be recorded as 0 when not imposed, since a right-hand-side value of 0 for an upper limit or equality constraint is extremely constraining. Treating these solutions as missing observations was not a viable option either, because these were valid data points even though some constraints were not imposed. Furthermore, treating them as missing data observations would reduce the number of usable observations to an unacceptably low level. This problem was handled as follows. Upper limit or equality constraints that were not present in all solutions were transformed to $1/C_j$, where C_j represents the right-hand-side value of the constraint in solution j. A value of 1 was used when an upper limit or equality constraint was not included in a solution. This transformation produced a variable whose values ranged from 0 to 1 (all values for C_j exceeded 1), thus avoiding the problem of a discontinuous variable or missing observations.

Early on it became obvious there was a high degree of collinearity among the constraints. Exact collinearity occurs if one variable is a linear combination of one or more of the other variables in the independent data set. As an example, two variables—X_1 and X_2—are exactly collinear if there exists a linear relationship, such as $X_2 = b_0 + b_1(X_1)$, which is true for all cases in the data (Weisberg 1980). In practice, such "exact collinearity" rarely occurs, and it is certainly not necessary for collinearity problems to exist (Belsley and others 1980). When two or more independent variables are collinear, the standard errors of the regression coefficients can become large. The estimates of the coefficients may be biased and the tests of significance become undependable due to the inflated standard errors.

A second but related problem is associated with measuring the effects of more than 100 independent variables with only 20 to 30 observations. This small number of observations limits the number of independent variables that can be identified in any one regression equation. Mathematically, the number of independent variables in any one regression cannot exceed the number of observations. But the number of independent variables required for statistical reliability is considerably less. Draper and Smith (1981) present the rule of thumb that there should be about 10 complete observations (degrees of freedom) for each variable to be estimated.

These problems made it necessary to reduce the number of independent variables in the data sets. The objective of the variable reduction process was to obtain a manageable list of constraint variables with correlations among themselves that were sufficiently low so as to avoid problems with collinearity and to try to reduce the disparity between the number of observations and the number of explanatory variables.

The first step was to eliminate the variables that were present in only several solutions as well as those variables that had the same value in each solution. It was apparent that these variables would not contribute to explaining variation in PNV.

In the next step, constraint variables were eliminated systematically so that no two variables in the remaining list of candidate variables had correlation coefficients of 0.9 or above. This was accomplished by listing each of the constraint variables in descending order according to their simple correlation with PNV. Each constraint variable

having a correlation of 0.9 or above with the first variable on the list was eliminated. Then, each constraint variable having a correlation of 0.9 or higher with the next (remaining) constraint variable on the list was exhausted. This process was continued until the entire list was processed. The result was a list of candidate constraint variables having the highest possible correlation with PNV and still having simple correlation coefficients among themselves less than 0.9.

The next step was to identify the extent of collinearity among the remaining independent variables. This was accomplished by calculating a variance inflation factor for each variable. The variance inflation factors are calculated as the diagonal elements of the inverse of the correlation matrix. A high variance inflation factor (say a value greater than 10) indicates that a high degree of collinearity exists among the independent variables. It, however, does not indicate which variables are the cause of this collinearity. (Readers are referred to Belsley and others 1980 for a complete discussion of variance inflation factors as well as other techniques for handling collinearity.)

If the presence of high collinearity was indicated by the variance inflation factors, the list of candidate constraint variables was pared down further. This second stage of variable reduction used a series of diagnostic regressions. In this process, each constraint variable was regressed against the set of remaining independent variables using stepwise regression procedures. Each of the diagnostic equations having adjusted R-squares of 0.9 and above was examined, and the dependent variable in that equation was deleted from the list of candidate variables. Eliminating this variable eliminates the source of collinearity between it and the significant independent variables in the equation (they are highly related as indicated by the high R-square), and yet most of the variation in the eliminated variable can still be represented by the remaining independent variables, which are not highly correlated among themselves. New variance inflation factors were calculated for the resulting list of candidate constraint variables. If collinearity was still present, this second stage of variable reduction was repeated until the collinearity was reduced to an acceptable level. The result of this process was a set of candidate variables that were used in an ordinary least squares regression modeling procedure.

The regression equations were developed using a stepwise regression approach in which variables enter the model one at a time in the order of their explanatory strength. At each step in the procedure, the variables currently in the model are tested for significance, and insignificant variables are removed.

OLS RESULTS AND DISCUSSION

The regression equations developed by fitting PNV as a function of constraint variables are presented in tables 1, 2, and 3. Both unstandardized regression coefficients (measured in the original units) and standardized regression coefficients (transformed to 0 mean and standard deviation of 1) are presented. Two of the three models represent reasonably good fits by standard statistical measures. These are the Beaverhead model (table 1), which contained

Table 1—Equations developed for the Beaverhead National Forest by fitting PNV as a function of constraints

Variables in equation[1]	Unstandardized coefficients	Standardized coefficients
LIMA1	41,800	0.375
P41S3	36,200	.653
P16S2	421	.299
P48S4	38,200	.828
(Constant)	–74,300	
R-square = 0.77	Adjusted R-square = 0.72	F = 15.4

[1]LIMA1 = upper-limit constraint placed on volume of timber that can be harvested in the Lima Mountain Range in decade 1, measured in millions of cubic feet.

P41S3 = the sum of the equality constraints that force water rehabilitation prescriptions to be allocated on a given number of acres across the Forest (measured in thousands of acres).

P16S2 = the sum of the equality constraints that force timber management prescriptions of medium intensity, visual quality objectives of modification or maximum modification, to be allocated on a given number of acres across the Forest (measured in thousands of acres).

P48S4 = the sum of the equality constraints that force nontimber summer range prescriptions for big game to be allocated on a given number of acres across the Forest (measured in thousands of acres).

Table 2—Equations developed for the Gallatin National Forest by fitting PNV as a function of constraints

Variables in equation	Unstandardized coefficients	Standardized coefficients
V16A04[1]	365	–0.470
(Constant)	297,000	
R-square = 0.22	Adjusted R-square = 0.19	F = 6.5

[1]V16A04 = the sum over mountain ranges of the upper-limit constraints placed on the volume of timber that can be harvested in decade 1, measured in millions of cubic feet.

Table 3—Equations developed for the Lolo National Forest by fitting PNV as a function of constraints

Variables in equation[1]	Unstandardized coefficients	Standardized coefficients
MATOLDLL	–0.792	–0.355
TM812	–29,200	–.366
WFOR1LL	–120	–.348
(Constant)	413,000	
R-square = 0.82	Adjusted R-square = 0.80	F = 29.9

[1]MATOLDLL = a lower-limit constraint placed on the mature old growth provided for wildlife species that are mature old-growth users, measured in thousands of acre equivalents.

TM812 = a dummy variable identifying when equality constraints were applied to force the allocation of specified amounts of grizzly bear habitat management, coded as 1 when these constraints were present and 0 when they were absent.

WFOR1LL = lower-limit constraint placed on the amount of winter forage for big game that is to be produced for decade 1, measured in thousands of animal unit months (AUM's) per decade.

four constraint variables explaining 77 percent of the variation in PNV, and the Lolo model (table 2), which included three constraint variables explaining 82 percent of the variation in PNV.

In the case of the Gallatin model (table 3), only one constraint variable was significant at the 10 percent level, and the regression equation explained 22 percent of the total variation in PNV. A major reason for such a poor fit was that few of the constraints were present in even half of the solutions, and thus the degree of variation in the explanatory variables was greatly reduced.

Let us now consider these models in view of one of the previously stated uses, that of interpretation. In this use, the regression coefficients are used as a measure of the per-unit effect the associated independent variable (constraint) has on the dependent variable (PNV). For example, in the Beaverhead equation, the unstandardized coefficient for LIMA1 (table 1) indicates that PNV would increase $41.8 million for a one-unit increase in LIMA1. The standardized coefficient can be used to examine the strength of the relationship. In this case the coefficient for LIMA1 indicates that it is the third most important variable in the equation.

There are, however, two major problems with using the regression coefficients in any of these models for interpretation purposes. First, recall that many of the original constraint variables were dropped because they were highly correlated with one or, in most cases, many of the other independent variables. (The problem of collinearity discussed earlier.) As a result, it is likely that the variables included in the above model are serving as proxies for the highly collinear variables that were dropped. Therefore, the regression coefficient of a particular variable measures not only the effects of that variable, but the joint effect of the set of correlated variables which it represents.

The second difficulty with using the regression coefficients for interpretation is that unless the independent variables included in a model are strictly independent (are not correlated with each other), the regression coefficient for any given variable may be influenced by which additional variables are included in the regression model. Therefore, to use the regression coefficients for interpretation purposes, one must assume that the model is correctly specified and make a judgment about the extent to which collinearity may influence the estimation of the coefficients. Given the fact that there are a large number of interrelated management constraints used in FORPLAN, and that these regression models include at most four variables, the probability that these regression models are correctly specified seems quite small. For this reason, plus the fact that the variables in the models are acting as proxy variables, these models appear to have little value for measuring the effect of specific constraints on PNV.

Prediction was the other stated use for these regression equations. Prediction has a distinctly different focus than does interpretation. Although interpretation uses the regression coefficients to quantify the relationship between a dependent and an independent variable, prediction is concerned with using the independent variables to predict values for the dependent variable. Collinearity and model misspecification are much less of a concern in prediction, because good predictions can still be made even when these conditions are present (Koutsoyiannis 1979). A major concern in prediction is that the sets of values for the independent variables from which PNV is predicted exhibit the same relationships that were present among these variables in the data from which the equations were developed. In other words, these equations should only be used to predict PNV for the types of management alternatives included in the original data. Given the complexity of each management alternative (hundreds of constraints), it is unlikely that the user would be able to ascertain whether a particular management alternative was similar to those used to develop the equations. Large errors are possible if PNV is predicted for a vastly different type of management alternative.

In most prediction applications, it is desirable to develop regression equations that reliably predict the dependent variable with as few independent variables as possible. This minimizes the amount of data that must be collected both for fitting the equation and applying the equation to predict the dependent variable. The situation here, as it turns out, is somewhat different. We would prefer more rather than fewer independent variables in a prediction equation, because this would allow us to predict PNV for more precisely defined management alternatives. As it is, PNV can be predicted only from four constraints in the Beaverhead model, one in the Gallatin model, and three in the Lolo model. It is not possible to predict PNV for a management alternative that involves specifying one or more constraints that are not present in these models, and this restricts the usefulness of these models for predictive purposes.

These regression models are constructed using the criterion that an independent variable had to be statistically significant at the 10 percent confidence level to be included in the regression equations. There is a school of thought that these criteria should be relaxed to much lower levels if a regression model is to be used solely for prediction purposes. It is argued that this would increase the number of independent variables included in the model and thus the accuracy of the fit. It is apparent, however, that the increases in the number of variables that are possible would only marginally improve the previously discussed problem. The number of variables permitted in a regression model is ultimately limited by the number of observations available in the original data. The number of observations (FORPLAN solutions) from which these equations were developed would have to be increased substantially before much improvement in this problem could be realized. To illustrate, say that there are 50 constraints of management importance (probably somewhat conservative based on the FORPLAN models we have seen). If the same ratio of number of independent variables to number of observations is maintained at about 10 observations per independent variable, 500 FORPLAN solutions would be required for a regression model to contain all 50 variables. This would be difficult, given the cost of producing those solutions.

THE PRINCIPAL COMPONENTS/ REGRESSION APPROACH

The problem, mentioned above, of being able to predict PNV based on only a small number of constraint variables may be solved to some extent through the use of principal components. In this approach, a principal component analysis would be performed on the complete set of constraint variables of interest. Then, a regression analysis would be done using the principal components as independent variables.

The objective of principal components analysis is to transform a set of variables into a new set of variables that are not correlated and capture as much of the variance of the original variables as possible. The first principal component is the linear combination of all of the variables which captures the greatest amount of variation in the data set. The second component is the linear combination of all of the variables, which has as much of the remaining variance as possible subject to being orthogonal (linearly unrelated) to the first and so on for the rest of the principal components.

Figure 1 illustrates the concept of principal components. X_1 and X_2 are two hypothetical variables. When plotted, the distribution of the observed values takes the form of an ellipse (fig. 1a). If a principal component analysis were to be performed, the first principal would be along the new axis labeled Y_1 (fig. 1b). Y_1 could be thought of as a variable comprised of both X_1 and X_2 (it could be represented mathematically as a function of X_1 and X_2). This dimension explains (or measures) the greatest amount of variation possible for a single dimension (the range of the distribution is greater along this new axis Y_1 than any other axis that could be drawn).

The second principal component in this example would be the new axis Y_2, which is orthogonal to Y_1. The distribution and dimensions Y_1 and Y_2 can be redrawn as illustrated in figure 1c, because Y_1 and Y_2 represent linear transformation of the original variables X_1 and X_2. Together, Y_1 and Y_2 account for 100 percent of the variation in the original variables, X_1 and X_2.

The advantage of the principal components combined with regression over classical regression analysis is its greater facility for handling large, highly interrelated sets of data. Because the principal components are orthogonal, the information provided by each is unique. Thus, the components are not linearly related, so the problem of collinearity in the regression portion of the analysis is eliminated. When the matrix of independent variables contains some variables that are perfect linear combinations of others (collinear), the regression problem cannot be solved, but by using the principal components regression technique, it is possible to estimate the regression parameters (Massy 1965). The principal components provide the same total information as the original variables, and any analysis between the variables which compose the principal components and any other variables can use the principal components with no loss of information.

Just as the principal components are defined as linear combinations of the original variables, the original variables can also be defined as linear combinations of the principal components, and there is a unique relationship

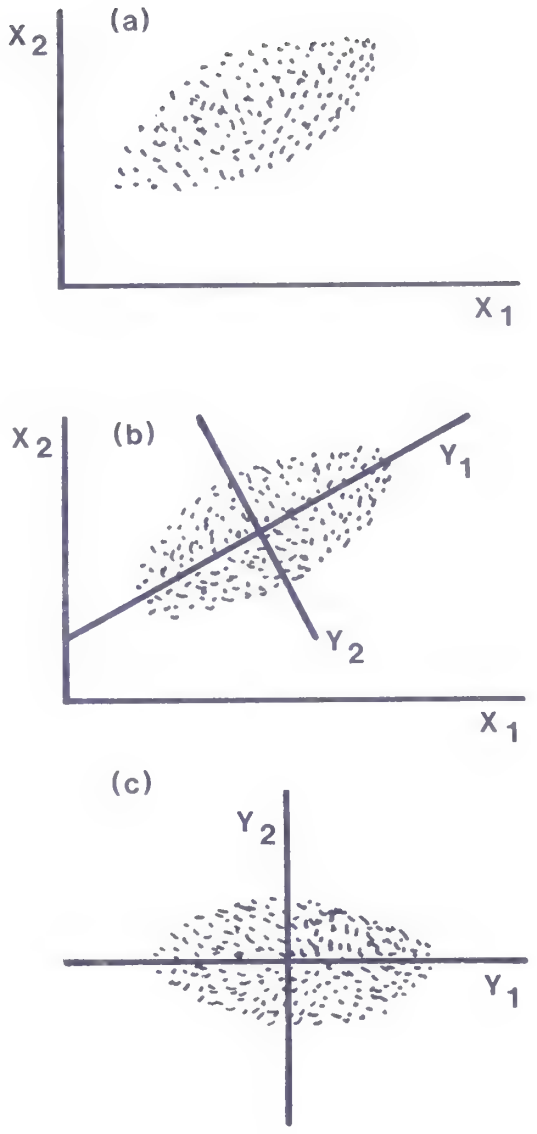


Figure 1—Example illustrating the basic concept underlying principal components: (a) is a plot of two hypothetical variables, X_1 and X_2; (b) Y_1 and Y_2 are the two principal components; and (c) shows rotating the axis so that Y_1 and Y_2 become, respectively, the ordinate and the abscissa.

between the coefficients on the principal components in the regression and the variables within the principal components. Thus the transformation of the regression coefficients back to the original variables yields the usual least squares solution for the beta coefficients of regression (Massy 1965). This entire process, however, has done nothing to reduce the inherent collinearity of the underlying data, and the resulting coefficients are still dependent on the variables included in the principal component analysis. What has improved is the accuracy with which the coefficients can be estimated by the regression procedure.

The first step in applying PCAR was to decide which constraint variables should be included in the principal

components. Recalling that there were about 100 constraint variables for each Forest, we excluded from the PCAR analysis those variables whose values had little to no variation across most FORPLAN solutions and variables which were not present in most solutions. The remaining variables (48 on the Beaverhead, 49 on the Lolo, and 15 on the Gallatin) were the variables potentially useful in explaining variation in PNV.

There are two bases for generating principal components, using the variance-covariance matrix and using the correlation matrix. We used the correlation matrix, which is more stable and should be used when the variables are measured in a variety of units such as occurred in this study. The other approach is sensitive to both units as well as scale and should be applied only when all the variables are measured the same.

Because initially there are as many principal components as original variables, not all of the principal components could be present simultaneously in a regression equation. Removing nonzero principal components reduces the amount of information to the regression. There are two criteria that can be used to determine which components to delete from the regression analysis (Massy 1965): (1) those principal components that have a low correlation with the dependent variable can be dropped, or (2) those principal components with the smallest eigenvalues (lowest variation) can be dropped. We used the latter criteria, dropping only those components with extremely small eigenvalues, so that as much of the variation in the original independent variables as possible was preserved in the principal components used.

One of the problems with principal components analysis is that there is no way of investigating whether a particular variable included in the PCAR is related to the dependent variable. And because using different numbers of variables or principal components gives substantially different results, it appears that including only relevant variables in the PCAR is very important. We excluded only variables that created problems in the data set, such as those that were constant, missing in most cases, or had very little variation across the data.

PCAR RESULTS AND DISCUSSION

The first step in the PCAR approach is to compute the principal components. Table 6 presents the eigenvectors for the 10 principal components computed for the Lolo (the constraint variables are defined in the appendix). These eigenvectors present each principal component as a function of the original constraint variables. The 10 principal components captured essentially all of the variation in the set of 49 constraint variables. In other words, these 10 principal components contain essentially the same information as do the original constraint variables.

Once the principal components were computed for each data point, the stepwise regression procedure used previously was applied to fit PNV as a function of the principal components. The model developed for the Lolo is presented in table 4. Three principal components significant at the 10 percent level are included in this model. The adjusted R-square for this model is 0.78.

A summary of the results from the PCAR approach is presented for all three Forests in table 5. As was the case in the OLS approach, a relatively good fit was obtained for the Lolo and Beaverhead cases (adjusted R-squares were 0.78 and 0.80, respectively), but a relatively poor fit was obtained for the Gallatin case (adjusted R-square of 0.20). A contributing factor on the Gallatin was that the two principal components in that model explained only 24 percent of the variation in the original constraint variables. For the Lolo and Beaverhead, the principal components included in the models captured much more variation in the original constraint variables, 82 and 83 percent, respectively.

In terms of the variation in PNV, the models containing the principal components as independent variables generally provided a modest improvement over the approach in which PNV was fit against the constraint variables themselves. The adjusted R-squares from both approaches are:

	OLS approach	PCAR approach
Beaverhead	0.72	0.80
Lolo	.80	.78
Gallatin	.19	.20

Table 4—Equations developed for the Lolo National Forest by fitting PNV as a function of principal components

Variables in equation[1]	Unstandardized coefficients	Standardized coefficients
PC1	–75.6	–0.643
PC3	–22.6	–.566
PC4	–10.8	–.270
R-square = 0.80	Adjusted R-square = 0.78	F = 27.7

[1]PC1, PC3, and PC4 = respectively, principal components 1, 2, and 4 that are calculated from the constraint variables as shown in table 6.

Table 5—Summary of results from fitting PNV as a function of principal components

Item	National Forest		
	Beaverhead	Lolo	Gallatin
R-square	0.92	0.81	0.26
Adjusted R-square	0.80	0.78	0.20
Number of constraint variables comprising the principal components	48	49	15
Number of principal components in the regression equations[1]	7	3	2
Percentage of the total variance in the original constraint variables accounted for by the principal components in the regression equations	82	83	24

[1]Principal components included in the regression equations are significant at the 10 percent confidence level.

The greatest improvement was observed for the Beaverhead, an increase of 8 percent; a 1 percent increase was observed for the Gallatin, and a slight drop occurred for the Lolo.

Interpreting the regression equation developed via the PCAR approach depends on one's ability to relate each principal component back to the original constraint variables. The key here is the coefficients in the eigenvectors that relate the constraint variables to the principal components (table 6).

If the coefficient of a constraint variable in the eigenvector is large, that variable strongly influences the principal component and is said to have a "high loading." When a principal component is composed mostly of variables of the same type of constraint, and the loadings of the others approach zero, then it is possible to interpret

Table 6—Conversion factors (called eigenvector elements) for computing the principal components for the original constraint variables for the Lolo National Forest

Constraint variables[1]	PC1	PC2	PC3	PC4	PC5
CV2	0.1627	0.0081	0.0020	–0.0880	0.1623
CV3	.1570	.0688	–.1184	.1059	–.0814
CV4	.1493	.1045	.1170	–.0481	–.2972
CV5	.0994	–.2971	–.0238	.0504	–.0720
CV6	.1574	.0694	–.1351	.0921	.0068
CV7	.1652	.0011	–.0348	.0028	.0099
CV8	.1590	–.0140	–.1361	.1184	–.0291
INVCV1	.1442	–.1795	–.0796	.0959	–.0418
DWHGEQ	.1540	.0884	.1054	–.0551	–.2412
INVAV4	.0359	.1219	.4021	–.4706	.1384
DWVAEQ	.1638	.0108	–.0770	.0236	.0627
INVKV16	.1589	–.0034	–.1388	.1191	–.0281
MATOLDLL	.0997	.0415	.3508	.3396	–.0717
INVCT21	.1132	.0213	.2835	.3285	–.0102
INVLN19	.1611	.0696	.0576	–.0662	–.0756
WFOR1LL	.0580	.0295	.3409	.4306	.1507
HCLL	.1461	.0995	.1369	–.0469	–.3509
INVNC11	.1088	–.1021	.3571	–.2514	–.2734
HGLL	.1536	.0872	.1094	–.0558	–.2495
RALL	.1640	–.0289	.0430	–.0682	.0107
NRARB	.1640	–.0291	.0430	–.0682	.0106
LINEFV18	.0885	–.3327	.0096	.0435	–.0463
RBLL	.0885	–.3327	.0096	.0435	–.0463
TBLL	.1196	.2509	–.1517	.0794	.0274
INVNHDL	.0885	–.3327	.0096	.0435	–.0463
INVHCL	.1442	–.1795	–.0796	.0959	–.0418
INVNH7	.1590	–.0143	–.1360	.1184	–.0291
INVIV19	–.0478	–.3469	–.1336	–.2154	.0107
INVEV19	.0208	–.3863	.0799	–.0416	–.0605
LINECV8	.1610	.0181	–.1045	.0966	–.0685
LINEEV20	.1231	.2471	–.1192	.0775	–.0555
LINEFV8	.1624	.0402	.0692	–.0730	–.0760
LINEAV8	.1635	.0263	–.0202	–.0589	.1319
DWRAEQ	.1615	.0424	–.1046	.0571	.0312
NHGMM	.1648	–.0046	.0156	–.0534	.0174
NHAVD	.1648	.0125	–.0028	–.0475	.0592
NHDUL	–.1551	.1256	.0106	–.0164	.1475
MNLL	.1632	–.0356	–.0168	–.0509	.1074
VCLL	.1637	–.0021	–.0134	–.0634	.1390
VDLL	.1630	.0035	–.0022	–.0807	.1552
TRELL	.1628	.0041	.0022	–.0871	.1609
VBLL	.1622	.0055	.0103	–.0988	.1713
NVAVD	.1623	.0060	.0079	–.0957	.1687
HBLL	.1633	.0110	–.0091	–.0734	.1498
VALL	.1613	.0130	.0181	–.1119	.1838
NHAHB	.1644	.0004	–.0474	–.0158	.0969
LEGHTV4	.1626	.0259	–.0069	–.0807	.1584
NUTBLL	.1625	.0464	–.0843	.0239	.0673
NDV2	–.0427	–.1248	.3465	.1828	.4357

(con.)

Table 6 (Con.)

Constraint variables[1]	PC6	PC7	PC8	PC9	PC10
CV2	0.0615	0.0093	–0.0379	0.0873	–0.0323
CV3	–.0951	–.0085	.1126	–.2259	.0533
CV4	–.1558	–.0656	–.0131	.0413	.0077
CV5	.0627	–.0596	–.5345	–.2419	.6687
CV6	–.0564	–.0014	.0608	–.0902	.0039
CV7	–.0202	–.0031	.0209	–.0065	–.0254
CV8	–.0580	.0052	.0894	–.1216	–.0189
INVCV1	–.0177	.0196	.0992	–.1086	–.0683
DWHGEQ	–.1282	–.0563	–.0162	.0486	.0008
INVAV4	.1139	.0338	.3551	–.6359	.1535
DWVAEQ	–.0054	.0060	.0291	–.0248	–.0212
INVKV16	–.0602	.0043	.0882	–.1217	–.0157
MATOLDLL	.2862	.3268	–.3470	–.2500	–.3758
INVCT21	.1316	.4857	.4340	.3525	.4821
INVLN19	–.0546	–.0308	–.0254	.0628	–.0087
WFOR1LL	.2332	–.7687	.1514	.0346	.0435
HCLL	–.1764	–.0728	–.0100	.0383	.0075
INVNC11	–.0463	–.0597	–.1044	.2310	–.0653
HGLL	–.1311	–.0574	–.0162	.0490	.0006
RALL	.0034	–.0073	–.0153	.0616	–.0402
NRARB	.0035	–.0073	–.0152	.0616	–.0402
LINEFV18	.0357	.0318	.0852	–.0644	–.1102
RBLL	.0357	.0318	.0852	–.0644	–.1102
TBLL	–.0818	–.0185	.0221	–.0662	.0633
INVNHDL	.0357	.0318	.0852	–.0644	–.1102
INVHCL	–.0177	.0196	.0992	–.1086	–.0683
INVNH7	–.0579	.0052	.0894	–.1216	–.0190
INVIV19	–.1069	–.1651	.2474	.1430	.1232
INVEV19	.0472	.0103	.0766	.0139	–.1287
LINECV8	–.0769	–.0066	.0741	–.0995	–.0109
LINEEV20	–.1148	–.0309	.0251	–.0669	.0625
LINEFV8	–.0467	–.0284	–.0248	.0678	–.0184
LINEAV8	.0382	.0068	–.0140	.0329	–.0138
DWRAEQ	–.0328	.0019	.0484	–.0685	–.0036
NHGMM	.0070	–.0244	–.1363	.0129	.1247
NHAVD	.0105	–.0084	–.0600	.1162	–.0294
NHDUL	.0815	.0293	–.0843	.0359	.0354
MNLL	.0537	–.0124	–.1726	.0002	.1627
VCLL	.0486	.0095	–.0214	.0619	–.0332
VDLL	.0580	.0095	–.0328	.0797	–.0330
TRELL	.0617	.0096	–.0368	.0862	–.0334
VBLL	.0684	.0098	–.0441	.0980	–.0340
NVAVD	.0664	.0097	–.0422	.0949	–.0335
HBLL	.0524	.0086	–.0295	.0727	–.0300
VALL	.0748	.0095	–.0531	.1116	–.0327
NHAHB	.0199	.0080	.0069	.0142	–.0281
LEGHTV4	.0542	.0075	–.0362	.0810	–.0262
NUTBLL	–.0116	.0028	.0237	–.0229	–.0103
NDV2	–.7873	.0700	–.1061	–.0507	–.0267

[1]The constraint variables are defined in the appendix.

the meaning of that principal component. For example, a principal component comprised of a high loading for a constraint variable measuring lower limits placed on timber harvesting and a high loading for a constraint that represents lower limits placed on forage production (with all other variables having low loadings) could be thought of as representing intensive forest management. The regression coefficient associated with that principal component would measure the relative effect of intensive management on PNV.

But high loadings on discernible groups of constraint variables with low loadings on others did not occur with any frequency on the three Forests tested in this study. The eigenvectors in table 6 illustrate quite well the patterns observed in this study—a range of loadings, some large, some medium, and some small, with no easily

identifiable pattern. As a result it is difficult to attach any interpretive meaning to the principal component obtained.

To predict PNV for a management alternative, one would first define the management alternative in terms of all the constraints to be imposed. These values would then be substituted into the eigenvector equations (shown for the Lolo in table 6) to compute the values for the principal components. The values for the principal components are then substituted into the regression equations to compute the predicted PNV.

The principal component approach provides the ability to predict PNV for much more precisely defined management alternatives (in terms of the constraints included) than does the OLS approach using the original variables. For example, on the Lolo, 49 constraint variables can be used to define a management alternative with the PCAR approach, while using the OLS approach a management alternative could only be defined using three constraint variables. One of the major restrictions that was discussed previously regarding the use of the OLS equations for predicting PNV also applies to the principal components equations. These equations should be used only to predict PNV for management alternatives that are similar to the alternatives (FORPLAN solutions) that comprised the data from which the equations were developed. In other words, the relationship between the constraints in a trial management alternative must be similar to those in the data used to develop the equations. A problem with this restriction is that there are so many dimensions to a typical planning problem that it is difficult to know when one is attempting to predict PNV for a management problem that is out of range for a prediction equation.

It seems that the interrelated nature of constraints that is present in linear programming models such as FORPLAN is a major problem underlying the general approach tested in this study. The effect of any one constraint on PNV depends on the level at which other constraints are imposed. Perhaps this point is best explained via a simple example. Figure 2 represents a simple linear programming problem having two outputs, X_1 and X_2. Two upper-limit constraints are imposed, C_1 and C_2, resulting in a feasible region OCBA. Assume now that an additional upper limit constraint, C_4, is imposed (fig. 3) and that the objective function has a slope that is less than the slope of C_4 but greater than the slope of C_1 (line BA in fig. 3). Then, the largest feasible value for the objective function would occur at the corner point Y_1. If constraint C_4 is relaxed (increased) to C_4', the optimal solution would instead occur at Y_2, and if moved to C_4'', would occur at A. But relaxing C_4 further so that it intersects the horizontal axis to the right of point A (as illustrated by C_4''' and C_4'''') would have no additional effect on the optimal solution. It would continue to stay at point A, where constraint C_1 is binding.

The optimal solution points identified in figure 3 are plotted against PNV in figure 4. The regression line that would result from regressing PNV against C_4 is included. Note that the relationship between C_4 and PNV is not linear. The rate of change in PNV associated with a unit change in C_4 depends on what other constraints are imposed. As a result, the regression line underestimates PNV in the middle of the distribution and overestimates

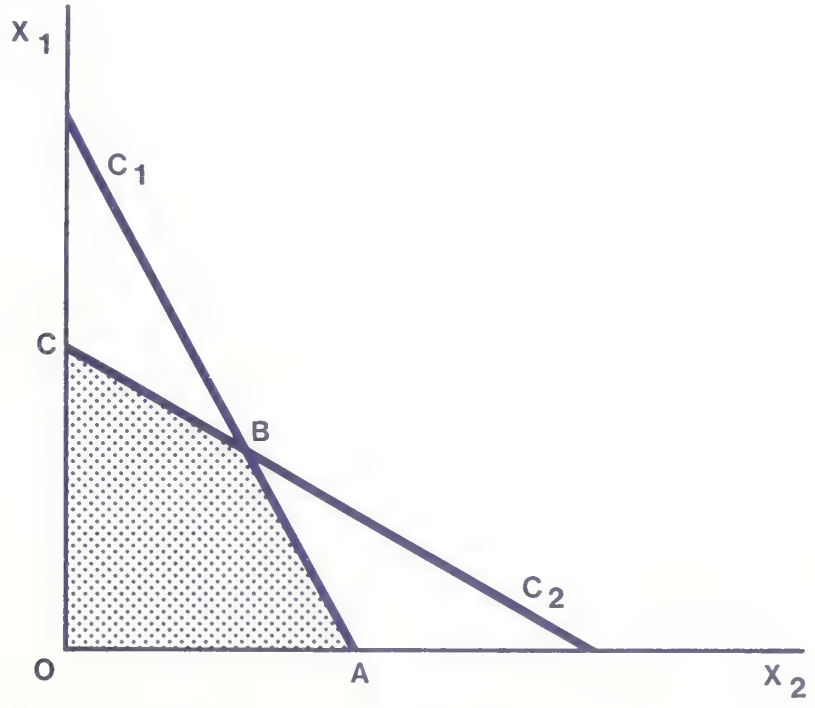


Figure 2—A hypothetical linear programming problem containing two output variables, X_1 and X_2, two upper-limit constraints, C_1 and C_2, and feasible region OCBA.

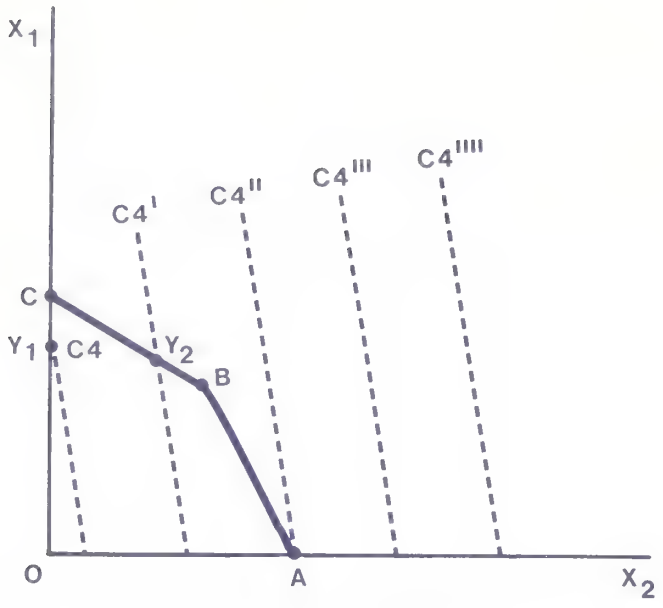


Figure 3—A series of hypothetical linear programming problems in which upper-limit constraint C_4 is systematically relaxed from C_4 to C_4''''.

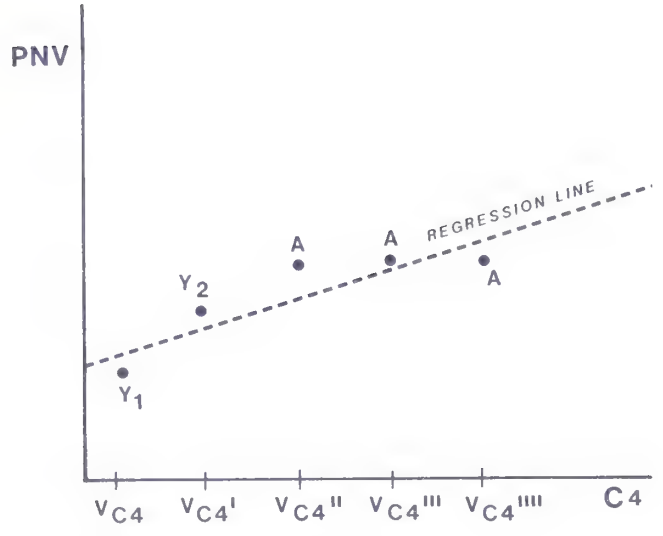


Figure 4—The right-hand-side values for the C_4 series of constraints (fig. 3) plotted against the maximum values for PNV.

on the ends. But there are worse scenarios. If C_1 and C_2 (fig. 2) were increased or decreased, or additional constraints were imposed, the relationship between PNV and C_4 in figure 4 could take on an entirely different shape. Again, the effect C_4 has on PNV depends on what other constraints are imposed.

It is believed that relationships such as these contribute to the large amount of collinearity observed in the test data sets. The result is difficulty in isolating the effect of any one constraint on PNV because that effect is not independent of a large number of other circumstances. These relationships also can cause problems in predicting PNV. Consider again the example presented in figures 2 through 4. Because the relationship between PNV and C_4 depends on what other constraints are imposed, and at what level they are imposed, any number of quite different regression lines could be obtained for PNV and C_4. In other words, the results could vary substantially, depending on what solutions comprise the data base. Furthermore, this problem is exacerbated by the fact that only a relatively small number of solutions would likely serve as the data base for the analysis. This emphasizes the importance of the statement made earlier that PNV should be predicted only for the same types of management alternatives present in the data used to develop a prediction equation.

CONCLUSIONS

The results indicate that the two approaches tested in this study do not reliably estimate the effect individual constraints have on PNV—the interpretative use of the regression coefficients. With the OLS approach, inherent collinearity among the constraints makes it difficult to correctly isolate the effect of any one constraint. Using principal component analysis with regression, relationships between the principal components and PNV can be accurately determined, but it is difficult to relate this information back to the original constraints.

For predictive purposes, these approaches fared only slightly better. With the OLS approach it was possible to have only a small fraction of the constraints in a predictive equation simultaneously. This severely limits their usefulness because they cannot be used directly to predict PNV for management alternatives that involve specifying constraints not present in the equations. The principal component approach improved this situation somewhat. Two of the three test models contain principal components comprised of about 50 constraints. This allows a much more precisely defined management alternative to be evaluated.

An important restriction, however, is present when using either OLS or principal component equations for prediction. The effect of any one constraint on PNV is generally determined by what other constraints are imposed. Thus, the equations should only be applied to predicting PNV for the same "types" of management alternatives that were present in the data used to develop those equations. Substantial errors could occur if PNV were to be predicted for a management alternative that involved a pattern of constraints that was not present in the original data. Given the many dimensions of a typical planning problem, this is a serious limitation. It is likely that it would be extremely difficult to identify when one is attempting to predict PNV for a management alternative (set of constraints) that contains substantially different constraint interrelations than the data used in developing the prediction equation.

A further problem affecting both the OLS and principal component approaches was the limited number of observations in the data. When there is a large number of variables relative to the number of observations, some of the variables are bound to be collinear just by chance.

Thus, collinearity problems can be expected to occur in sample data even when collinearity is not present in the population being sampled. Second, because the number of data points is small, only a small portion of the decision space is represented in the data. Moreover, there is reason to believe that the data points sampled are not well distributed across the decision space. Sets of very similar solutions were typically made in developing a forest plan alternative, giving rise to clusters of data points. This restricts the range of management alternatives for which the equations can reliably predict PNV.

A further consideration is that the application of this approach requires a substantial amount of resources. A large quantity of information must be extracted from each FORPLAN solution and coded into workable constraint variables. In addition, a good knowledge of statistical model building techniques (particularly techniques for dealing with collinearity) is needed.

It is clear that a number of problems exist in the approaches tested in this study. As a result, we believe the methods have very limited applicability. In view of this, and in view of the resources and expertise required, the approaches of fitting PNV as a function of constraints either directly with OLS or indirectly with principal components, cannot be recommended for either prediction or interpretation purposes.

REFERENCES

Bell, Enoch F.; Randall, Robert M. 1982. Opportunities to increase national forest softwood harvest. Journal of Forestry. 80: 152-156, 160.

Belsley, David A.; Kuh, Edwin; Welsch, Roy E. 1980. Regression diagnostics: identifying influential data and sources of collinearity. New York: John Wiley and Sons. 292 p.

Draper, N. R.; Smith, H. 1981. Applied regression analysis. New York: John Wiley and Sons. 709 p.

Fight, Roger D.; Randall, Robert M. 1980. Visual quality and the cost of growing timber. Journal of Forestry. 78: 546-548.

Fight, Roger D.; Johnson, K. Norman; Connaughton, Kent P.; Sassaman, Robert W. 1978 (rev.). Roadless area-intensive management tradeoffs on western National Forests. Washington, DC: U.S. Department of Agriculture, Forest Service. 57 p.

Hughes, Joy M. 1965. Economic choice and wilderness land allocation. Paper presented to Forestry Section, Northwest Scientific Association Meeting, Portland, OR. 14 p.

Jones, J. Greg; Beardsley, Wendell G.; Countryman, David W.; Schweitzer, Dennis L. 1978. Estimating economic costs of allocating land to wilderness. Forest Science. 24: 410-422.

Kemper, Robert E.; Davis, Lawrence S. 1976. Costs of environmental constraints of timber harvesting and regeneration. Journal of Forestry. 74: 754-761.

Koutsoyiannis, A. 1979. Theory of econometrics. London: The Maximillian Press. 681 p.

MacCleery, Douglas. 1982. Expectations of the Secretary's Office related to National Forest land management planning. Speech given at Regional Foresters and Directors Meeting; 1982 January; Phoenix, AZ. Washington, DC: U.S. Department of Agriculture, Forest Service. 9 p.

Massy, William F. 1965. Principal components regression in exploratory statistical research. Journal of The American Statistical Association. 60: 234-256.

Weisberg, Sanford. 1980. Applied linear regression. New York: John Wiley and Sons. 283 p.

APPENDIX: DEFINITION OF CONSTRAINT VARIABLES USED IN THE PRINCIPAL COMPONENT ANALYSIS CONDUCTED USING FORPLAN SOLUTIONS FROM THE LOLO NATIONAL FOREST

Variable name	Description
PNV	Present net value for a FORPLAN solution measured in thousands of dollars.
CV2	The sum of prescription constraints that specify the thousands of acres to be allocated to deer and elk winter range habitat management without regulated timber, in habitat groups 2, 3, and 6.
CV3	The sum of prescription constraints that specify the thousands of acres to be allocated to grizzly bear habitat management in habitat groups 2, 3, 4, and 5.
CV4	The sum of prescription constraints that specify the thousands of acres to be allocated to old-growth management in habitat groups 2, 3, and 6.
CV5	The sum of prescription constraints that specify the thousands of acres to be allocated to minimum maintenance management on habitat groups 2, 3, 4, and 5.
CV6	The sum of prescription constraints that specify the thousands of acres to be allocated to roadless-dispersed recreation management, including no development or off-road vehicles on habitat groups 0, 2, 3, and 6.
CV7	The sum of prescription constraints that specify the thousands of acres to be allocated to roadless-dispersed recreation management, including no development or off-road vehicles on habitat groups 4 and 5.
CV8	The sum of prescription constraints that specify the thousands of acres to be allocated to a partial retention visual quality objective, with regulated timber on habitat groups 2, 3, and 4.
INVCV1	One divided by the sum of prescription constraints that place an upper limit on the thousands of acres that could be allocated to grizzly bear habitat management on habitat groups 1 and 6.
DWHGEQ	The forestwide sum of prescription constraints that specify the thousands of acres to be allocated to old-growth management.
INVAV4	One divided by the sum of prescription constraints that specify the thousands of acres to be allocated to minimum maintenance management on habitat group 1.
DWVAEQ	The forestwide sum of prescription constraints that specify the thousands of acres to be allocated to regulated timber management, with a retention visual quality objective.
INVKV16	One divided by the sum of prescription constraints that specify the thousands of acres to be allocated to regulated timber and wildlife habitat management having a retention visual quality objective on habitat groups 2 and 3.
MATOLDLL	A lower-limit constraint on the thousands of acre-equivalents of old-growth habitat created for wildlife species that use old-growth.
INVCT21	One divided by the upper limit placed on the amount of timber (units?) that can be clearcut in period 1 on habitat groups 2 and 3.
INVLN19	One divided by the upper limit placed on old-growth management in habitat group 1.
WFORILL	A lower-limit constraint placed on the amount of winter forage for big game (thousands of animal unit months) that is to be produced in decade 1.
HCLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to key elk summer habitat management.
INVNC11	One divided by the sum of prescription constraints that specify the upper limits on the thousands of acres that can be allocated to grizzly bear habitat management in habitat group 4.
HGLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to old-growth management.
RALL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to management for roadless-dispersed recreation in which no development is present and no off-road vehicles are allowed.
NRARB	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to (1) management for roadless-dispersed recreation in which no development is present and no

(con.)

APPENDIX (Con.)

Variable name	Description
	off-road vehicles are allowed, and (2) management for roadless-dispersed recreation in which no timber harvesting is allowed, but off-road vehicles are allowed.
LINEFV18	The sum of all prescription constraints placing a lower limit on the thousands of acres that are to be allocated to management for roadless-dispersed recreation in which no timber harvesting is present and off-road vehicles are allowed in habitat group 5.
RBLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to management for roadless-dispersed recreation in which no development is present and off-road vehicles area allowed.
TBLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to moderate intensity timber management, without local roads, and with soil constraints.
INVNHDL	One divided by the forestwide sum of all upper-limit prescription constraints placed on the thousands of acres to be allocated to grizzly bear habitat management.
INVHCL	One divided by the forestwide sum of all upper-limit prescription constraints placed on the thousands of acres to be allocated to key elk summer range habitat management.
INVNH7	One divided by the sum of all upper-limit prescription constraints placed on the thousands of acres to be allocated to grizzly bear habitat management in habitat group 6.
INVIV19	One divided by the sum of the upper-limit prescription constraints placed on the thousands of acres to be allocated to grizzly bear habitat management in habitat groups 2 and 3.
INVEV19	One divided by the sum of the upper-limit prescription constraints placed on the thousands of acres to be allocated to key elk summer habitat management in habitat group 6.
LINECV8	The sum of prescription constraints placed on the thousands of acres that are to be allocated to key elk summer habitat management in habitat group 4.
LINEEV20	The sum of prescription constraints placed on the thousands of acres that are to be allocated to key elk summer habitat management in habitat group 6.
LINEFV8	The sum of prescription constraints placed on the thousands of acres that are to be allocated to old-growth management in habitat group 5.
LINEAV8	The sum of prescription constraints placed on the thousands of acres that are to be allocated to management for roadless-dispersed recreation in which no development is present and no off-road vehicles are allowed in habitat group 1.
DWRAEQ	The forestwide sum of all prescription constraints placed on the thousands of acres that are to be allocated to management for roadless-dispersed recreation in which no development and no off-road vehicles are allowed.
NHGMM	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to (1) old-growth management, and (2) minimum maintenance management.
NHAVD	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to: (1) Deer and elk winter range habitat management, with regulated timber (2) Deer and elk winter range habitat management, without regulated timber (3) Key elk summer habitat management (4) Grizzly bear habitat management (5) Old-growth management (6) Minimum maintenance management (7) Management for roadless-dispersed recreation in which no development or off-road vehicles are allowed (8) Management for roadless-dispersed recreation in which timber harvesting is not permitted, but off-road vehicles are allowed (9) Management for dispersed recreation in roaded areas (10) Timber management with a retention visual quality objective (11) Timber management with a partial retention visual quality objective (12) Timber and wildlife habitat management with a retention visual management objective (13) Timber and wildlife habitat management with a partial retention visual management objective.

(con.)

APPENDIX (Con.)

Variable name	Description
NHDUL	The forestwide sum of all upper-limit prescription constraints placed on the thousands of acres to be allocated to grizzly bear habitat management.
MMLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to minimum maintenance management.
VCLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to regulated timber and wildlife habitat management having a visual quality objective of retention.
VDLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to regulated timber and wildlife habitat management having a visual quality objective of partial retention.
TRELL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to management for dispersed recreation in roaded areas.
VBLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to regulated timber management having a visual quality objective of partial retention.
NVAVD	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to: (1) Timber management with a retention visual quality objective (2) Timber management with a partial retention visual quality objective (3) Timber and wildlife habitat management with a retention visual management objective (4) Timber and wildlife habitat management with a partial retention visual management objective.
HBLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to deer and elk winter range habitat management without regulated timber.
VALL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to regulated timber management having a visual quality objective of retention.
NHAHB	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to deer and elk winter range habitat management both with and without regulated timber.
LEGHTV4	The forestwide sum of prescription constraints placed on the thousands of acres to be allocated to deer and elk winter range habitat management, with regulated timber in habitat group 1.
NUTBLL	The forestwide sum of all lower-limit prescription constraints placed on the thousands of acres to be allocated to moderate intensity timber management, without local road, and with soil constraints.
NDY2	Dummy variable identifying the presence of the nondeclining yield constraints on timber harvest, coded as: 0: nondeclining yield constraints absent 1: nondeclining yield constraints present.

Hyde, James F. C., III; Jones, J. Greg; Meacham, Mary L. 1988. Evaluating statistical techniques for predicting and interpreting FORPLAN results. Res. Pap. INT-395. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 14 p.

Two approaches using multiple linear regression for analyzing the effects of management constraints on an objective function in FORPLAN were tested on three National Forests. The two approaches, ordinary least squares regression and ordinary least squares using principal components, provide some degree of success in predicting objective function values, but very little information for interpreting the effects of the constraints on objective function values.

KEYWORDS: forest planning, applied regression analysis, land management planning

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-396

December 1988

Lodgepole Pine Vigor, Regeneration, and Infestation by Mountain Pine Beetle Following Partial Cutting on the Shoshone National Forest, Wyoming

Gene D. Amman
Gene D. Lessard
Lynn A. Rasmussen
Curtis G. O'Neil

THE AUTHORS

GENE D. AMMAN is principal entomologist and Project Leader, Mountain Pine Beetle Population Dynamics research work unit, Intermountain Research Station, Ogden, UT.

GENE D. LESSARD at the time of this study was entomologist, Forest Pest Management, Rocky Mountain Region, Forest Service, U.S. Department of Agriculture, Lakewood, CO. He is now Group Leader, Forest Pest Management, Alaska Region, Forest Service, U.S. Department of Agriculture, Anchorage.

LYNN A. RASMUSSEN is biological technician, Mountain Pine Beetle Population Dynamics research work unit, Intermountain Research Station, Ogden, UT.

CURTIS G. O'NEIL is entomologist, Forest Pest Management, Rocky Mountain Region, Lakewood, CO.

RESEARCH SUMMARY

Lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) stands were thinned in the Shoshone National Forest of northwestern Wyoming in 1979 and 1980 using different forms of partial cutting to determine if losses to mountain pine beetles (*Dendroctonus ponderosae* Hopkins) could be reduced by such treatment. Forms of partial cutting used were (1) remove all trees ≥7 inches diameter at breast height (d.b.h.); (2) remove all trees ≥10 inches d.b.h.; (3) remove all trees ≥12 inches d.b.h.; (4) spaced thinnings that kept about 50 of the best trees; and (5) no cutting. Average losses of trees 5 inches d.b.h. and larger during the 5 years following thinning ranged from less than 1 percent in the spaced thinnings to 7.4 percent in the 12-inch diameter limit cut, compared to 26.5 percent in check stands. Regeneration 5 years after thinning ranged between 1,160 and 3,560 seedlings per acre, with pine being favored in the more open stands. Residual trees increased radial growth significantly during the first 5 years following thinning. However, many trees should have remained susceptible to mountain pine beetle infestation because of large diameter and low growth efficiency. Changes in microclimate of thinned stands are suspected of affecting beetle behavior and hence of reducing numbers of infested trees.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Lodgepole Pine Vigor, Regeneration, and Infestation by Mountain Pine Beetle Following Partial Cutting on the Shoshone National Forest, Wyoming

Gene D. Amman
Gene D. Lessard
Lynn A. Rasmussen
Curtis G. O'Neil

INTRODUCTION

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) continues to kill millions of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) annually in the Western United States and Western Canada. In terms of trees killed by forest insects, MPB frequently ranks at the top of the list and is the foremost tree killer of lodgepole pine (Loomis and others 1985; Sterner and Davidson 1982).

Until about 1970, the principal way of treating MPB infestations was through direct control, consisting of applying insecticide to infested trees or felling and burning infested trees (Klein 1978; Safranyik and others 1974). At best, these proved to be short-term holding actions until trees could be harvested. Generally, unless susceptible trees are harvested immediately, MPB infestations will continue in stands treated with insecticides, and within a few years losses are such that remaining timber cannot be harvested economically (Amman and Baker 1972). Harvesting susceptible trees or modifying stand conditions that are conducive to MPB infestation (McGregor and others 1987) are the only long-term solutions to the MPB problem. Therefore, silvicultural methods that are preventive in their action should be emphasized.

Clearcutting may be the preferred silvicultural option for the majority of high-risk lodgepole pine stands in a specific drainage. However, concern for other resource values (namely, riparian areas, wildlife hiding, thermal and escape cover, watershed protection, and view areas) limits the amount of clearcutting and frequently permits only partial treatment of many susceptible stands (Bollenbacher and Gibson 1986). These concerns lead managers to ask for other options that might reduce stand susceptibility to the beetle, yet be compatible with management of other resource values. Partial cutting (Alexander 1986) offers promise for meeting these objectives.

Partial cutting to reduce losses of lodgepole pine to MPB was first tested in Colorado in 1972 (Cahill 1978). Treatment consisted of removing large-diameter trees to which MPB is attracted (Shepherd 1966). The thicker phloem (food for developing larvae) in larger trees usually results in high beetle production (Amman 1972). The partial cuts resulted in minimal tree losses to MPB (1 to 2 percent), compared to losses in unthinned stands (>30 percent).

Subsequent to the Colorado work, four partial cutting treatments were tested near West Yellowstone, MT (Hamel 1978). In three treatments, all trees larger than three specific diameter at breast height (d.b.h.) limits were removed: ≥7 inches and larger, ≥10 inches and larger, and ≥12 inches and larger. The fourth treatment was based on phloem thickness, where all trees having phloem ≥0.1 inch were removed. Compared to check stands, tree mortality was much less in partial cuts based on diameter limits but was about the same when cutting was based on phloem thickness.

Another form of partial cutting, consisting of spacing to leave residual basal areas (BA) of 80, 100, and 120 ft^2/acre was studied along with diameter limit cuts starting in 1976 in the Kootenai and Lolo National Forests, MT. Losses of trees 5 inches and larger d.b.h. ranged from 4.0 to 38.6 percent in the Kootenai and 6.0 to 17.1 percent in the Lolo, compared to 93.8 and 73.1 percent, respectively, in check stands. Only the 120-ft^2 BA/acre treatment had large losses (38.6 percent) (McGregor and others 1987). In addition to diameter limit cuts, another form of partial cutting consisting of spaced thinnings leaving the best trees in the stands was studied on the Shoshone National Forest, WY (Cole and others 1983). Although tree mortality remained low 1 year after all thinnings were completed, tree losses were greater in check than in partial cut stands (Cole and others 1983), but a longer period of beetle pressure was necessary for differences among treatments to be manifested.

This paper reports on the first 5 years' results of the Shoshone study. The principal objective of this study was to test the effectiveness of partial cutting for reducing losses to MPB in the Shoshone National Forest, where lodgepole pine growth was slow and stands were heavily infected with dwarf mistletoe (*Arceuthobium americanum*

Nutt. ex Engelm.) and comandra blister rust (*Cronartium comandrae* Pk.) (Rasmussen 1987). Treatments consisted of three levels of diameter limit cuts and a spaced thinning. In addition, tree growth response, tree vigor, and regeneration were studied.

METHODS

The study area lies primarily in the East Long Creek drainage west of Dubois, WY, on the Shoshone National Forest. The elevation ranges from 7,600 to 8,800 ft, the lower half of the forested zone in the Wind River drainage. The climate is cool and dry; moisture availability is the most limiting growth factor during the season. Cole and others (1983) outline details of the study site, such as soils, habitat types, and stand characteristics before installation of treatments. Site index values for lodgepole pine in this area are 30 to 50 ft in 50 years.

Treatments consisted of two partial cuttings, one of which had three levels, and unthinned checks. These were randomly assigned to stands. Partial cutting began in January 1979 and was completed in February 1981. Treatments that we intended to test were one level of spaced thinning that was to leave the best 100 trees per acre as judged by size, form, and crown (two stands); and three levels of diameter limit cuttings and spaced thinnings. However, time constraints precluded sampling all initially selected stands. Therefore, several stands among each treatment were selected at random for surveying. These were:

Five of original 10 stands in the 7-inch diameter limit cuts
Nine of 17 stands in the 10-inch diameter limit cuts
Two of two stands in the 12-inch diameter limit cuts
Two of two stands in the spaced thinnings
Two check stands

Average diameter of trees in the 7-inch cuts averaged 7.6 inches d.b.h., the lower end of the 8-inch diameter class. Therefore, some trees in the stands were larger than the 7-inch class. The spaced thinnings contained about 50 trees per acre rather than 100 following thinning.

Using a double sampling scheme, stands were sampled in the fall of 1985, 5 years after the partial cuts were made, to obtain estimates of living and infested trees. Variable plots (10 BA factor) were used to sample green stand structure. The plots were 5 chains apart and were located in a grid pattern. The number of plots per stand was proportional to stand size and ranged from two to 10 per stand. An angle gauge was used to determine trees to be tallied. The diameter of all trees 5 inches d.b.h. and larger was measured, and trees were categorized as live, killed by MPB, or killed by other causes. The two live trees closest to plot center were measured for height and crown length, and two increment cores 180 degrees apart were taken from each for determining age and obtaining vigor measurements. A strip survey 1 chain wide was used to sample trees killed by MPB. All dead trees on the strip were tallied by cause of death, and the same measurements taken as on live trees in the variable plots. Study data were also used to evaluate performance in managed stands of the Cole and McGregor (1983) model developed for predicting tree losses to MPB in unmanaged stands.

From 1980 to 1985, d.b.h. and two measures of tree vigor—periodic growth ratio and grams of stemwood produced per square meter of foliage—were evaluated for change. In addition, leaf area was included to aid in interpretation of findings. Because so few lodgepole pines were killed by MPB, an extensive comparison of infested and uninfested trees such as that done by Amman and others (1988) was not possible. Therefore, tree size and vigor for live trees were compared between 1981 and 1985 and among treatments.

Vigor of trees was based on two measurements. One is growth efficiency expressed as grams of stemwood produced per unit of foliage (Waring and others 1980). Foliage is estimated from sapwood area: 1 inch^2 sapwood equals 1.16 yd^2 of foliage (Waring and others 1982). The second is periodic growth ratio (PGR), which is the current 5 years' radial stem growth divided by the previous 5 years' radial stem growth (Mahoney 1978). Regeneration plots for seedlings and saplings consisted of 1/100-acre plots, using the same center as each variable plot. All trees >1 inch d.b.h. were tallied by species.

Analysis of variance (ANOVA) (SAS procedure GLM for unequal numbers of observations) was used to analyze growth and tree vigor data among treatments and between years within treatments. Covariance analysis was included to analyze radial growth before (the covariate) with growth after treatment. Tukey's Studentized Range Test was used to test for significant differences ($P < 0.05$) among means.

RESULTS AND DISCUSSION

All stands in 1985 had average diameters of close to or exceeding the 8-inch average specified for stand susceptibility to MPB infestation (Amman and others 1977; Safranyik and others 1974). However, tree losses to MPB among treatments were significantly greater in check stands than all other treatments. Tree mortality did not differ significantly among the partial cutting treatments ($P > 0.05$).

Tree Losses to Mountain Pine Beetle

Five years after cutting, check stands had sustained 26.5 percent lodgepole mortality, the largest increase occurring in 1985. Tree mortality in treated stands ranged from 0.3 percent in the spaced thinnings to 7.4 percent in the 12-inch diameter limit cut (table 1; fig. 1). Thus, partial cutting appears to be highly effective in reducing losses to MPB. Although losses among treatments did not differ significantly, the trend is for greater losses where cutting was less.

Table 1—Lodgepole pine mortality caused by mountain pine beetles in partial cutting treatments, East Long Creek, Shoshone National Forest, WY

Treatment	Year							1979 to 1985	1981 to 1985	Percent killed 1981-85
	1979	1980[1]	1981	1982[2]	1983	1984	1985			
	Trees per acre									
7-inch	0.72	0.51	0.09	0.04	0	0.50	0	1.86	0.63	1.8
10-inch	.35	.66	.07	.20	.33	.85	.62	3.08	2.07	2.4
12-inch	.19	5.00	1.15	.74	.33	.67	.17	8.25	3.06	7.4
Spaced	.20	.10	.10	0	0	0	0	.30	.10	.3
Check	2.53	5.77	4.23	3.74	3.25	2.75	9.50	31.77	23.47	26.5

[1]Partial cuts were made in 1979 and 1980.
[2]Estimated by using the average of 1981 and 1983.

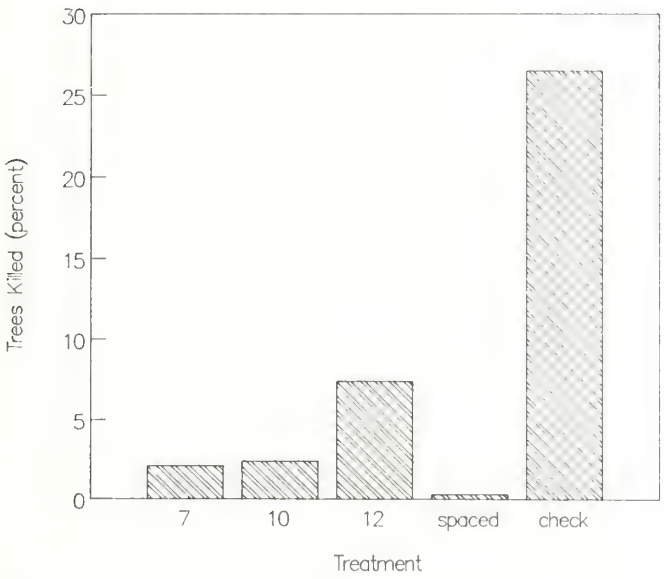


Figure 1—Lodgepole pine losses to mountain pine beetle during 1981 to 1985, the 5 years after partial cutting treatments were applied, Shoshone National Forest, WY.

Table 2—Actual and predicted annual lodgepole pine mortality per acre to mountain pine beetle for the first 5 years following partial cutting treatments, East Long Creek, Shoshone National Forest, WY, 1985

Treatment	Annual loss		Actual as a percentage of predicted annual loss
	Predicted	Actual	
	- - Trees per acre - -		
7-inch	2.50	0.13	5.2
10-inch	2.40	.41	17.1
12-inch	4.40	.61	13.9
Spaced	.70	.02	2.9
Check	12.90	4.69	36.4

Annual tree mortality (trees per acre per year) from MPB predicted by the Cole and McGregor model (1983) (table 2) was substantially greater than actual loss in all treatments. Annual tree mortality in the check stands averaged 4.69 trees per acre compared to predicted losses of 12.90 trees per acre, or about 36 percent of predicted losses. The difference between predicted and actual losses is inversely proportional to the intensity of partial cutting. The Cole and McGregor (1983) model was developed for unmanaged lodgepole pine stands at lower elevations in Montana. Therefore, the difference between actual and predicted mortality values on the Shoshone National Forest probably is related to treatment effects and, in the case of check stands, the relatively high elevation of the stands for that latitude (7,600 to 8,800 ft). Hence, the stands are not as susceptible as lower elevation stands (Amman and others 1977). In addition, heavy dwarf mistletoe infection in the stands (Rasmussen 1987) may have reduced tree vigor and resulted in phloem too thin to attract and support higher beetle populations. McGregor (1978) observed less loss of lodgepole pine to MPB as dwarf mistletoe infection increased in the Gallatin National Forest in southwestern Montana.

Characteristics of Residual Stands

Number of trees per acre for all species ranged between 46.3 in the spaced thinning to 104.6 in the 10-inch diameter limit cuts (table 3). A large percentage of the residual trees was lodgepole. The check stands still had 65 lodgepole pines per acre after losing over 30 lodgepole pines per acre to MPB. Although the 10-inch diameter limit cuts contain more trees than the checks, differences in mortality probably reflect the effects of opening up the treated stand. Changes in stand microclimate as a result of tree harvest (Bartos and Amman in press), as well as removal of some of the larger diameter trees, probably affected beetle behavior, as observed in partial cuts in Montana (Schmitz and others in press), resulting in reduced infestation.

Table 3—Average number of trees and basal area per acre (trees ≥5 inches d.b.h.) in partial cut stands by tree species and treatment, East Long Creek, Shoshone National Forest, WY, 1985

Treatment	Tree species: Lodgepole pine	Limber pine	Subalpine fir	Douglas-fir	Aspen	Total all species	Basal area: $\bar{x}$	Basal area: sd	Lodgepole d.b.h.
7-inch	34.4	3.7	17.9			56.0	21.9	13.7	8.0
10-inch	84.7	6.6	1.1	2.9	9.3	104.6	41.1	17.1	8.6
12-inch	38.2	15.5	6.7	1.8	12.7	74.9	32.4	6.2	7.9
Spaced	37.4		8.9			46.3	35.0	7.1	10.5
Check	65.0	8.0	2.7		3.8	79.5	42.0	5.7	11.2

Posttreatment basal areas per acre of all species (1985) ranged from about 22 ft² BA for the 7-inch diameter limit cuts to 42 ft² BA for the checks (table 3). Basal areas were light even for the check stands. The most consistent difference among treatments was in tree diameter. Average d.b.h. of lodgepole in the check was significantly larger ($P < 0.05$) ($\bar{x}$ = 11.2 inches) than all other treatments. Trees in the spaced thinning had the second largest diameters ($\bar{x}$ = 10.5 inches) (table 3).

In the diameter limit cuts, d.b.h of trees, which ranged between 7.9 and 8.6 inches, did not differ significantly ($P > 0.05$). The large diameter of trees in the check stands probably is a significant factor in the continued infestation in those stands. Diameter was found to be an important factor in susceptibility of lodgepole to infestation in natural stands (Cole and Amman 1969; Stuart 1984), as well as in partially cut stands on the Kootenai and Lolo National Forests (Amman and others 1988). However, the fact that the spaced thinnings had average d.b.h. almost as large as the check stands points to the probable role of microclimate in reducing losses to MPB in thinnings (Bartos and Amman in press).

Growth Response

ANOVA revealed a significant difference in growth among stands before the treatments were applied ($P < 0.05$). For the 1976 to 1979 period, the treatments tended to separate (Tukey's Studentized Range Test) into two groups significant from one another. An exception was the 10-inch diameter limit cut that appeared in both groups. Group 1 consisted of the 7-inch and 10-inch treatments, and group 2 consisted of the check, 10-inch, 12-inch, and spaced thinnings.

Following treatment, growth response was significantly different among treatments ($P < 0.05$), with the covariate (radial growth before treatment) also significant ($P < 0.05$) (fig. 2). Growth following treatment also separated into two significantly different groups. Group 1 consisted of the 12-inch diameter limit cuts and spaced thinnings. Group 2 consisted of the 7-inch and 10-inch diameter limit cuts, and check stands (table 4). Trees in all treatments had substantial live crowns with averages ranging between 46 and 63 percent of total tree height

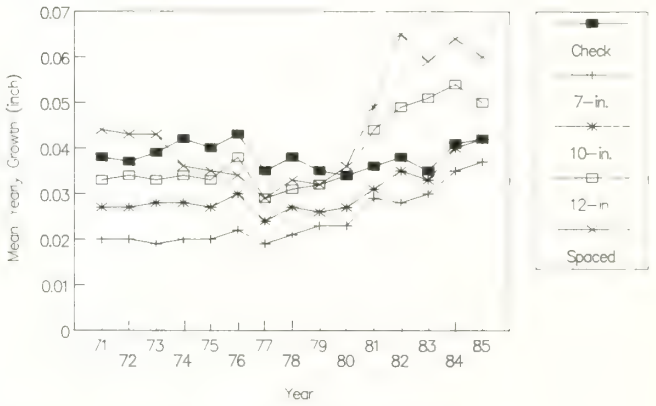


Figure 2—Radial growth of lodgepole pine before (1971 to 1980) and after (1981 to 1985) partial cutting treatments, East Long Creek, Shoshone National Forest, WY.

(table 4). Therefore, trees had ample capacity to respond with increased growth following thinning. Only the check stands did not respond with a significant increase in growth ($P > 0.05$); however, the trend is up. Apparently, increases in numbers of trees killed by MPB were not large enough to provide growth response as rapid as partial cutting treatments, even though crown ratios in the check stands were similar to those of residual trees in the partial cut stands. Extensive tree mortality in check stands in the Kootenai and Lolo resulted in significant growth response of residual trees (Amman and others 1988).

Regeneration

Regeneration averages ranged from 1,160 trees per acre in the 12-inch diameter limit cuts to 3,650 trees per acre in the spaced thinnings (table 5). The pine species were generally more abundant in the spacing, 7-inch and 10-inch diameter limit cuts. The more tolerant conifers (Douglas-fir, subalpine fir, and spruce) were more abundant than pine in the 12-inch and check treatments. Figure 3 shows the relationship between treatment and tolerance of regenerated species, excluding aspen. (The check unit contained more aspen inclusions initially than

Table 4—Radial stem growth of lodgepole pine, before and after partial cutting treatments, and percent live crown, Shoshone National Forest, WY

Treatment	Growth				Live crown
	1976 to 1979		1982 to 1985		
	Total	Average annual	Total	Average annual	
	Inches				*Percent*
7-inch	0.083 a[1]	0.021	0.127 a	0.032	46.5
10-inch	.100 a,b	.025	.146 a	.037	54.8
12-inch	.127 b	.032	.200 b	.050	63.4
Spaced	.129 b	.032	.248 b	.062	51.1
Check	.129 b	.032	.138 a	.035	60.6

[1]Averages within a column followed by the same letter are not significantly different; those followed by different letters are significantly different, α 0.05.

Table 5—Regeneration (trees <1 inch d.b.h.) by tree species in partial cut stands, East Long Creek, Shoshone National Forest, WY, 1985

Treatment	Lodgepole pine	Limber and whitebark pine	Aspen	Douglas-fir	Spruce	Subalpine fir	Total
	Trees per acre						
7-inch	2,014	186	0	0	6	537	2,743
10-inch	1,796	243	8	33	41	143	2,264
12-inch	390	120	0	350	0	300	1,160
Spaced	3,250	275	0	0	0	125	3,650
Check	468	84	853	105	126	953	2,589

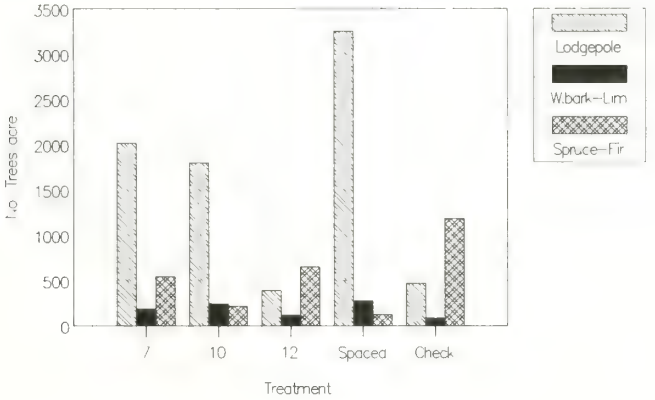


Figure 3—Regeneration of shade-tolerant and intolerant species per acre (all trees 1 inch d.b.h.) 5 years after stands received partial cutting treatments, East Long Creek, Shoshone National Forest, WY, 1985.

the treated units. Openings caused by the mountain pine beetle could stimulate root suckering in aspen.) In all cases, adequate numbers of seedlings and saplings are available for the next stand, should the manager decide to do an overstory removal at this time. Most regeneration is too short to provide hiding and thermal cover for big game. However, there is a tradeoff between big game cover and health of the next stand. Because of the heavy dwarf mistletoe infection, removal of the overstory at this time would prevent extensive infection of the regeneration.

Tree Vigor

ANOVA of change in d.b.h. between 1980 and 1985 shows a significant difference among treatments ($P < 0.05$). Tukey's Studentized Range Test shows no significant difference among means for the check, 7-inch, and 10-inch diameter limit cuts, and no difference between means for the 12-inch diameter limit and spaced thinnings ($P > 0.05$). However, the two groups of thinnings differed significantly ($P < 0.05$). These changes ranged between an average of 0.31 inch in the 7-inch diameter limit cuts to 0.59 inch in the spaced thinnings. As expected, the largest gains in growth occurred in the stands that were thinned substantially, but that also left many of the dominant and codominant trees in the residual stands.

For 1980, PGR's did not differ significantly among treatments ($P > 0.05$). However, large changes occurred by 1985. Only the PGR's for the unthinned check stands were significantly less than those of other treatments ($P < 0.05$). PGR's were significantly greater ($P < 0.002$) in 1985 than 1980 for all treatments except the check and 10-inch diameter limit cuts ($P \geq 0.09$). PGR's in 1985 ranged between 1.13 for the checks and 1.74 for the spaced thinnings, in contrast to a range between 1.02 for the spaced thinning and 1.25 for the 10-inch diameter limit cuts in 1980 (table 6).

Increase in PGR in a stand is indicative of increasing tree vigor. Average PGR's exceeding 1.00 for all treatments both in 1980 and 1985 suggest that all stands were resistant to infestation by MPB. The dividing point between susceptible stands and those resistant to MPB is 0.9 (Mahoney 1978). PGR's for trees killed by MPB in the check stand averaged 0.9, and the trees killed in the spaced thinning had a PGR of 1.1. Therefore, even the check stands should have been resistant to MPB. However, MPB continued to kill trees at an increasing rate during the past 5 years.

Grams of wood per square meter of foliage in 1980 were significantly different ($P < 0.05$) among treatments. Tukey's test identified only two differences: check ($\bar{x} = 54.7$ g) compared to 12-inch diameter limit cuts ($\bar{x} = 47.0$ g), and 7-inch diameter limit cuts ($\bar{x} = 56.3$ g) compared to the 12-inch diameter limit cuts. Because grams of stemwood per square meter of foliage and leaf area were significantly different in 1980, a covariance analysis of data obtained in 1985 would have been appropriate to account for these 1980 differences. However, data were obtained in different sets of trees in 1980 and 1985. Therefore, a covariance analysis was deemed inappropriate. One-way ANOVA between 1980 and 1985 data was used to determine if significant changes had occurred within treatments but not between treatments. ANOVA between years showed only the 12-inch diameter limit

Table 6—Diameter at breast height, grams of stemwood per square meter of foliage, periodic growth ratio, and leaf area in 1980 and 1985 for residual trees in lodgepole pine stands receiving different partial cutting treatments, East Long Creek, Shoshone National Forest, WY

Treatment	Number of observations		Diameter at breast height (inches)					Grams of wood				
			1980		1985			1980		1985		
	1980	1985	$\bar{x}$	sd	$\bar{x}$	sd	$P>F$	$\bar{x}$	sd	$\bar{x}$	sd	$P>F$
7-inch	22	90	7.6a[1]	1.92	8.0a[1]	1.89	[2]0.001	56.3a[1]	79.0	59.1	37.7	[2]0.808
10-inch	46	132	8.3a	1.90	8.6a	1.88	.001	69.8ab	57.2	57.1	36.4	.083
12-inch	36	38	7.4a	1.97	7.9a	1.86	.001	47.0a	21.2	68.6	41.1	.006
Spaced	34	14	9.9b	2.49	10.5b	2.44	.001	68.1ab	29.2	70.1	41.3	.850
Check	45	34	10.9ab	2.06	11.2b	2.11	.001	54.7a	52.8	63.3	37.6	.420

Treatment	Periodic growth ratio					Leaf area (m^2)				
	1980		1985			1980		1985		
	$\bar{x}$	sd	$\bar{x}$	sd	$P>F$	$\bar{x}$	sd	$\bar{x}$	sd	$P>F$
7-inch	1.03a[1]	0.33	1.59a[1]	0.81	[2]0.002	26.3a[1]	12.8	27.8	14.8	[2]0.665
10-inch	1.25a	.62	1.45a	.72	.088	26.6a	11.7	36.1	18.1	.001
12-inch	1.04a	.33	1.44a	.57	.001	39.7c	13.0	31.0	15.0	.009
Spaced	1.02a	.28	1.74a	.75	.001	41.7b	22.9	55.1	31.1	.106
Check	1.07a	.65	1.13b	.36	.655	49.5b	29.4	50.6	24.3	.853

[1]ANOVA was used to compare treatments by year.
[2]One-way ANOVA used between years by treatment.

cuts had a significant change in stemwood production per unit of foliage (1980$\bar{x}$ = 47.0; 1985$\bar{x}$ = 68.6).

These results suggest that changes in stemwood production per unit of foliage are slow. Even though wood production per unit of foliage did not differ among the check, 7-inch, and 10-inch treatments, only the check showed an increase in mortality to MPB. Therefore, wood production per unit of foliage does not appear to reflect very well the substantial increase in stem growth. This is perplexing, because the calculations should be highly sensitive to changes in width of the most recent growth ring. One possibility is that rings being dropped from the inner part of the sapwood and added to heartwood have area similar to the most recent outside ring added to the sapwood, thereby maintaining a fairly constant wood production per unit of sapwood (equivalent to foliage). Support for this idea is furnished by comparisons of leaf area measurements for 1980 and 1985.

ANOVA showed that significant differences ($P < 0.05$) in leaf area occurred only in the 10-inch diameter limit cuts (1980$\bar{x}$ = 26.6 m^2; 1985$\bar{x}$ = 36.1 m^2) and the 12-inch diameter limit cuts (1980 $\bar{x}$ = 39.8 m^2; 1985 $\bar{x}$ = 31.0 m^2) (table 6). In the 10-inch diameter limit cuts, leaf area increased but wood production decreased. This is consistent with the scenario that root growth increases first, followed by crown, and finally by stemwood (Waring 1983). However, in the 12-inch diameter limit cuts, the opposite occurred: leaf area showed a decline but stemwood increased. The 12-inch diameter limit cut was opened up more than the 10-inch diameter limit cut, as indicated by residual stocking. Possibly a greater loss of shade needles occurred, accompanied by a corresponding reduction in sapwood area in the 12-inch cut. This would have shifted the area ratio of current radial growth to sapwood area so that more wood per unit of foliage was produced in 1985 than in 1980.

On a stand basis, d.b.h. and vigor measurements do not account for differences in tree mortality. The average d.b.h. of the check stands is not significantly larger than that of the spaced thinnings, which suffered little or no loss. PGR, while less in the check than in other treatments, was still above 1.00. Wood production per leaf area unit in check stands was intermediate among treatments, while leaf area was among the highest. We suspect that change in microclimate of partial cut stands is a contributing factor (as Amman and others [1988] also hypothesized) for loss differences observed in thinnings on the Kootenai and Lolo National Forests. In the Kootenai and Lolo stands, changes in tree vigor as measured by PGR and grams of wood did not account for differences in tree mortality between thinned and unthinned stands. In the Kootenai and Lolo thinnings, large numbers of beetles were trapped in passive barrier traps, indicating many beetles were flying in the stands but few were infesting trees (Schmitz and others in press). The large beetle populations on the Kootenai and Lolo compared to the Shoshone, as indicated by tree mortality in the check stands (Kootenai = 93.8 percent; Lolo = 73.4 percent; Shoshone = 31.8 percent), showed that partial cuts were effective even when subjected to large beetle populations. At the same time, vigor ratings of residual trees indicated the stands were still highly susceptible to beetle infestation.

CONCLUSIONS

1. Partial cutting lodgepole pine stands significantly reduced lodgepole pine losses to mountain pine beetles.

2. Residual trees in thinned stands responded with a significant increase in diameter growth.

3. Regeneration 5 years after thinning was adequate for overstory removal.

4. Both thinned and unthinned stands remained susceptible to MPB infestation based on diameter and vigor ratings of residual trees.

REFERENCES

Alexander, Robert R. 1986. Silvicultural systems and cutting methods for old-growth lodgepole pine forests in the Central Rocky Mountains. Gen. Tech. Rep. RM-127. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 31 p.

Amman, Gene D. 1972. Mountain pine beetle brood production in relation to thickness of lodgepole pine phloem. Journal of Economic Entomology. 65: 138-140.

Amman, Gene D.; Baker, Bruce H. 1972. Mountain pine beetle influence on lodgepole pine stand structure. Journal of Forestry. 7: 204-209.

Amman, Gene D.; McGregor, Mark D.; Cahill, Donn B.; Klein, William H. 1977. Guidelines for reducing losses of lodgepole pine to the mountain pine beetle in unmanaged stands in the Rocky Mountains. Gen. Tech. Rep. INT-36. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 19 p.

Amman, Gene D.; McGregor, Mark D.; Schmitz, Richard F.; Oakes, Robert D. 1988. Susceptibility of lodgepole pine to infestation by mountain pine beetles following partial cutting of stands. Canadian Journal of Forest Research. 18: 688-695.

Bartos, Dale L.; Amman, Gene D. [In press]. Microclimate, an alternative to lodgepole pine vigor as a basis for mountain pine beetle, *Dendroctonus ponderosae*, infestation. Research Paper. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station.

Bollenbacher, B.; Gibson, K. E. 1986. Mountain pine beetle: a land manager's perspective. Rep. 86-15. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region. 5 p.

Cahill, Donn B. 1978. Cutting strategies as control measures of the mountain pine beetle in lodgepole pine in Colorado. In: Berryman, Alan A.; Amman, Gene D.; Stark, Ronald W., eds. Theory and practice of mountain pine beetle management in lodgepole pine forests: Symposium proceedings; 1978 April 25-27; Pullman, WA. Moscow, ID: University of Idaho, Forest, Wildlife and Range Experiment Station: 188-191.

Cole, Walter E.; Amman, Gene D. 1969. Mountain pine beetle infestations in relation to lodgepole pine diameters. Res. Note INT-95. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 7 p.

Cole, Walter E.; Amman, Gene D.; Jensen, Chester E. 1976. Mathematical models for the mountain pine beetle-lodgepole pine interaction. Environmental Entomology. 5: 11-19.

Cole, Walter E.; Cahill, Donn B.; Lessard, Gene D. 1983. Harvesting strategies for management of mountain pine beetle infestations in lodgepole pine: preliminary evaluation, East Long Creek demonstration area, Shoshone National Forest, Wyoming. Res. Note INT-333. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 11 p.

Cole, Walter E.; McGregor, Mark D. 1983. Estimating the rate and amount of tree loss from a mountain pine beetle infestation. Res. Pap. INT-318. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Hamel, Dennis R. 1978. Results of harvesting strategies for management of mountain pine beetle infestation in lodgepole pine on the Gallatin National Forest, Montana. In: Berryman, Alan A.; Amman, Gene D.; Stark, Ronald W., eds. Theory and practice of mountain pine beetle management in lodgepole pine forests: Symposium proceedings; 1978 April 25-27; Pullman, WA. Moscow, ID: University of Idaho, Forest, Wildlife and Range Experiment Station: 192-196.

Klein, William H. 1978. Strategies and methods for reducing losses in lodgepole pine by the mountain pine beetle by chemical and mechanical means. In: Berryman, Alan A.; Amman, Gene D.; Stark, Ronald W., eds. Theory and practice of mountain pine beetle management in lodgepole pine forests: Symposium proceedings; 1978 April 25-27; Pullman, WA. Moscow, ID: University of Idaho, Forest, Wildlife and Range Experiment Station: 148-158.

Loomis, Robert C.; Tucker, Susan; Hofacker, Thomas H. 1985. Insect and disease conditions in the United States, 1979-83. Gen. Tech. Rep. WO-46. Washington, DC: U.S. Department of Agriculture, Forest Service. 93 p.

Mahoney, R. B. 1978. Lodgepole pine/mountain pine beetle risk classification methods and their application. In: Berryman, Alan A.; Amman, Gene D.; Stark, Ronald W., eds. Theory and practice of mountain pine beetle management in lodgepole pine forests: Symposium proceedings; 1978 April 25-27; Pullman, WA. Moscow, ID: University of Idaho, Forest, Wildlife and Range Experiment Station: 106-113.

McGregor, Mark D. 1978. Management of mountain pine beetle in lodgepole pine stands in the Rocky Mountain area. In: Berryman, Alan A.; Amman, Gene D.; Stark, Ronald W., eds. Theory and practice of mountain pine beetle management in lodgepole pine forests: Symposium proceedings; 1978 April 25-27; Pullman, WA. Moscow, ID: University of Idaho, Forest, Wildlife and Range Experiment Station: 106-113.

McGregor, Mark D.; Amman, Gene D.; Schmitz, Richard F.; Oakes, Robert D. 1987. Partial cutting lodgepole pine stands to reduce losses to the mountain pine beetle. Canadian Journal of Forest Research. 17: 1234-1239.

Rasmussen, Lynn A. 1987. Mountain pine beetle selection of dwarf mistletoe and comandra blister rust infected lodgepole pine. Res. Note INT-367. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 3 p.

Safranyik, L.; Shrimpton, D. M.; Whitney, H. S. 1974. Management of lodgepole pine to reduce losses from the mountain pine beetle. Tech. Rep. 1. Victoria, BC: Canadian Department of the Environment, Forestry Service, Pacific Forest Research Centre. 24 p.

Schmitz, Richard F.; McGregor, Mark D.; Amman, Gene D. [In press]. Effect of partial cutting treatments of lodgepole pine on the abundance and behavior of flying mountain pine beetles. Canadian Journal of Forest Research.

Shepherd, R. F. 1966. Factors influencing the orientation and rates of activity of *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae). Canadian Entomologist. 98: 507-518.

Sterner, T. E.; Davidson, A. G. 1982. Forest insect and disease conditions in Canada 1981. Ottawa: Environment Canada, Canadian Forestry Service. 46 p.

Stuart, J. D. 1984. Hazard rating of lodgepole pine stands to mountain pine beetle outbreaks in southcentral Oregon. Canadian Journal of Forest Research. 14: 666-671.

Waring, R. H. 1983. Estimating forest growth and efficiency in relation to canopy leaf area. Advances in Ecological Research. 13: 327-354.

Waring, R. H.; Schroeder, P. E.; Oren, R. 1982. Application of the pipe model theory to predict canopy leaf area. Canadian Journal of Forest Research. 12: 556-560.

Waring, R. H.; Thies, W. G.; Muscato, D. 1980. Stem growth per unit of leaf area: a measure of tree vigor. Forest Science. 26: 112-117.

Amman, Gene D.; Lessard, Gene D.; Rasmussen, Lynn A.; O'Neil, Curtis G. 1988. Lodgepole pine vigor, regeneration, and infestation by mountain pine beetle following partial cutting on the Shoshone National Forest, Wyoming. Res. Pap. INT-396. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 8 p.

Lodgepole pine stands were thinned in the Shoshone National Forest of northwestern Wyoming in 1979 and 1980 using different forms of partial cutting. Average losses of trees 5 inches diameter at breast height and larger to mountain pine beetles during the 5 years following thinning ranged from less than 1 percent in spaced thinnings to 7.4 percent in the 12-inch diameter limit cut, compared to 26.5 percent in check stands. Residual trees increased radial growth significantly, but change in growth efficiency is slow. Regeneration 5 years after thinning ranged between 1,160 and 3,560 seedlings per acre, with pine being favored in the more open stands.

KEYWORDS: *Dendroctonus ponderosae, Pinus contorta*

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-397

January 1989

Revegetation by Land Imprinter and Rangeland Drill

Warren P. Clary

THE AUTHOR

WARREN P. CLARY is project leader of the Intermountain Research Station's Riparian-Stream Ecology and Management research work unit at Boise, ID. He received a B.S. degree in agriculture from the University of Nebraska, and an M.S. degree in Range Management and a Ph.D. in botany (plant ecology) from Colorado State University. He joined the Forest Service in 1960 and has conducted research on forested and nonforested rangelands in Arizona, Louisiana, Utah, Idaho, Oregon, and Nevada.

RESEARCH SUMMARY

The land imprinter and rangeland drill were compared for revegetation of a wildfire burn in the Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) vegetation type. Seeding trials were conducted on strips 152 m wide and 1.6 km long. Seeded species were fairway wheatgrass (*Agropyron cristatum*), luna pubescent wheatgrass (*A. trichophorum*), Russian wildrye (*Elymus junceus*), and Ladak alfalfa (*Medicago sativa*). Severe wind erosion on the study area occurred the first spring. Total seeded plant densities and cover were significantly higher with the imprinting treatment. Production of seeded plants was higher on the imprinted areas the first 2 years; thereafter, compensatory growth within the thinner drilled stand resulted in similar production levels between treatments. There was little difference in seeded plant establishment between soils.

ACKNOWLEDGMENTS

Appreciation is expressed to Thane J. Johnson (retired) and others of the Bureau of Land Management, U.S. Department of the Interior, who assisted in the establishment of this study.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Revegetation by Land Imprinter and Rangeland Drill

Warren P. Clary

INTRODUCTION

Rehabilitation of rangelands by seeding began in the Western United States in the late 1800's (Heady 1975). There is a long history of successes and failures. More literature exists on range seeding than any other practice in range management.

Numerous factors affect seeding success and should be considered in seeding prescriptions (Plummer and others 1968). Matching the plant species seeded to the climate and soil conditions is a critical concern in seeding success. Seeding depth and removal of plant competition are also important. The form or geometric pattern of the soil surface generally has received little thought in most revegetation projects, although various types of equipment have been developed to modify the shape of the soil surface as part of a revegetation effort (Anderson and others 1957).

Researchers have developed a technique called "land imprinting" by which simple machines imprint land surfaces with geometric patterns (Dixon and Simanton 1980). The developers of the technique suggested it had several advantages compared to conventional tillage implements, including the ability to increase depression water storage without inverting the soil surface, to increase effective surface mulch by concentrating all aboveground plant materials at the soil surface, and to impress the soil surface with geometric patterns for better control of infiltration, runoff, and erosion.

Seeding can be done by broadcasting ahead of the imprinter to permit the machine to firmly press the seed into contact with the soil (Anderson 1981), or by broadcasting following imprinting so that splash erosion will cover the seed in the imprinted depressions (Dixon and Simanton 1977).

Relatively little has been published in recent years comparing the effectiveness of different revegetation techniques (Clary and Wagstaff 1987), although several studies of imprinter results have been conducted in various locations (Cox and others 1986; Ganskopp 1985; Haferkamp and others 1987). The purpose of this study was to compare the revegetation effectiveness of a rangeland imprinter with that of a standard rangeland seeding technique—the rangeland drill (Vallentine 1971)—on a Great Basin wildfire burn.

STUDY AREA

In July 1981 lightning ignited two major fires in the Canyon Mountains area of central Utah. These fires, the Clay Springs and Little Oak Creek burns, covered approximately 25,000 ha in the pinyon-juniper (*Pinus* spp.-*Juniperus* spp.) and big sagebrush (*Artemisia tridentata*) vegetation types. The lands burned were predominately under Federal management—Forest Service, U.S. Department of Agriculture, and Bureau of Land Management, U.S. Department of the Interior.

The area selected for study was in the center of the Little Oak Creek burn on Bureau of Land Management land in the Wyoming big sagebrush (*Artemisia tridentata* spp. *wyomingensis)* vegetation zone at an elevation of approximately 1,550 m. The consumption of organic material by the fire was virtually complete, resulting in removal of all competing plants and debris from the soil surface. After several days of high winds most of the ashes were gone from the soil surface, leaving a seedbed of bare mineral soil requiring no additional preparation for seeding.

The soils were of the Shadbliss, Genola, and Renol series formed on alluvium from sandstone, limestone, quartzite, and igneous rocks. Brief descriptions are:

Shadbliss - These are shallow, well-drained soils with a pale brown fine sandy loam surface layer 10 cm thick. Effective rooting depth is 25 to 51 cm.

Genola - These are very deep, well-drained soils with a surface layer of light brownish gray silt loam about 15 cm thick. Effective rooting depth is 152 cm or more.

Renol - These are moderately deep, well-drained soils with a surface layer of brown stony fine sandy loam and gravelly loam about 23 cm thick. Effective rooting depth is 51 to 102 cm.

Principal herbaceous plant species found on the area include:

Grasses - western wheatgrass (*Agropyron smithii*), cheatgrass (*Bromus tectorum*), Indian ricegrass (*Oryzopsis hymenoides*), and bottlebrush squirreltail (*Sitanion hystrix*).

Forbs - pinnate tansymustard (*Descurainia pinnata*), gilia (*Gilia* spp.), prickly lettuce (*Lactuca serriola*), annual stickseed (*Lappula occidentalis*), coyote tobacco (*Nicotiana attenuata*), Russian-thistle (*Salsola iberica*), tumblemustard (*Sisymbrium altissimum*), and gooseberryleaf globemallow (*Sphaeralcea grossulariaefolia*).

METHODS

Revegetation Treatment

We established the study in October 1981. The treatments of imprinting and drilling were each replicated twice. Treatment strips were 152 m wide and 1.6 km

Figure 1—The land imprinter with seedbox drive.

Table 1—Average precipitation at nearby communities of Oak City and Scipio

Water year	Months												
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Total
	mm												
1982	111	22	28	39	14	55	13	37	7	26	28	124	504
1983	62	29	53	26	40	68	50	58	10	16	76	51	539
1984	29	84	79	15	19	55	46	16	80	61	38	21	543

long. The bulk seed mixture applied by both revegetation techniques consisted of fairway wheatgrass (*Agropyron cristatum*) 4.5 kg/ha, luna pubescent wheatgrass (*Agropyron trichophorum*) 1.7 kg/ha, Russian wildrye (*Elymus junceus*) 2.2 kg/ha, and Ladak alfalfa (*Medicago sativa*) 0.6 kg/ha, for a total of 9 kg of seed per hectare.

The land imprinter (fig. 1) was privately constructed using discarded 1.52-m asphalt rollers for the cylindrical base (Johnson 1982). Angle irons (20 cm long) were welded symmetrically around the cylinders. The cylinders were coupled by a steel frame with a tongue for pulling. The two cylinders combined were 3 m in width and almost 1.8 m in height. Each unit had a plugged access hole to allow the addition of liquid if additional weight was needed. A grain drill seedbox was mounted in front of the rollers to broadcast seed ahead of the imprinting. The seedbox was driven by a 25-cm rubber tire mounted to run directly against the side of the roller. This imprinter, without added water, weighed about 7.3 metric tons. In this trial no liquid was added because total depth impressions (approximately 15 cm) were attained without additional weight. A diesel-powered, rubber-tired tractor was used to pull the imprinter approximately 8 km per hour.

Rangeland drills 3 m wide were used as a standard revegetation technique for seeding comparisons with the land imprinter. The drill rows cut to a depth of 3 to 6 cm in these light-textured soils. Neither depth bands nor chain drags were used. Rate of travel varied from 5 to 8 km per hour.

Annual precipitation measured by weather observers in nearby communities ranged from 504 to 543 mm for the 3 years of study, which was 160 to 172 percent of the long-term mean for these weather stations (table 1). An estimate of the long-term average precipitation at the study area is 250 to 300 mm.

Measurements

Because the three soils transversed all treatment strips, vegetation was sampled on all three. The basic sample units were 30-m transects along which 10 plots of 1 m^2 each were uniformly spaced on alternate sides of the center line. In 1982 three transects were located within each

soil series in each strip. In 1983 and 1984 this was increased to five transects. Ocular estimates of green weight by plant species were made on each square-meter plot. Two plots per transect were randomly selected and a plot 3 m outside each was ocularly estimated and clipped. The clipped herbage was ovendried and weighed. Correction factors for the categories of perennial grasses, annual grasses, and forbs were calculated to convert green weight estimates to a dry weight basis.

Estimates of lightly compressed foliage cover by species were made on each 1-m^2 plot using the following percentage categories: 0.01-1.0, 1.1-5.0, 5.1-25.0, 25.1-50.0, 50.1-75.0, 75.1-95.0, and 95.1-100. Plant density counts were recorded for all perennial plant species within the 1-m^2 plots.

The level of the soil surface was marked on iron stakes at the first, fifth, and tenth plots of three transects per soil per strip to serve as a reference point for measurement of potential soil losses. Penetrability of the soil surface was determined with a pocket penetrometer. This characteristic was used as an index of soil bulk density.

Analysis

The data were converted to logarithms to normalize the distribution. Initial analyses by analysis of variance showed little effect of soils on seeded plant establishment. Therefore, plant data were pooled across soils for comparisons between imprinting and drilling. Tests of significance determined if the ratio of the revegetation treatments differed from 1. Analyses of variance determined if soil erosion losses and soil penetrability (index of bulk density) were related to soil series or revegetation technique.

RESULTS

Seedling establishment was not spectacular under either revegetation technique because of severe wind erosion that occurred primarily in late winter and spring 1982. However, the results did show a differential in establishment between techniques under these conditions.

Density

Initial density of seeded grasses was approximately 3.8 times higher on the imprinted strips than on the drilled strips (table 2). This advantage had decreased to 2.2 times by the third year after seeding, but the difference continued to be statistically significant. The seeded forb (alfalfa) had increased its ratio of plant densities from a nonsignificant 2.0 in the first year to a significant 4.0 in the third year in favor of the imprinting treatment, although the total number of plants remained low.

Establishment of crested wheatgrass and pubescent wheatgrass was quite successful in the initial stand (1982). These two species represented 96 percent of the seeded stand composition, whereas Russian wildrye was not found and Ladak alfalfa was poorly represented. By the second year the density of individual species was in approximate proportion to its weight of seed in the seed mixture with the exception of Russian wildrye, which was still missing on most plots. The proportion of alfalfa in the composition declined in the third year. Crested wheatgrass was the only individual species with densities significantly greater on the imprinted strips than on the drilled strips the first year after seeding. By the third year density of all seeded species except Russian wildrye were significantly greater in the imprinted treatment.

Cover

Comparisons of total foliage cover follow the general pattern seen for density (table 3). The advantage of seeded grass foliage cover in favor of the imprinted treatment remained significant in all years. Foliage cover of the seeded forb was significantly higher for the imprinted treatment in 1984 only.

Trends of cover for individual seeded species generally followed the trends for their densities. Crested wheatgrass had greater cover on imprinted strips than on drilled strips in all 3 years. Cover of pubescent wheatgrass was significantly greater on imprinted strips in 1983 and cover of Ladak alfalfa was greater in 1984.

Table 2—Comparison of seeded species densities between imprinted and drilled treatments

Species	1982		1983		1984	
	Imprint	Drill	Imprint	Drill	Imprint	Drill
	---------- *No./m^2* ----------					
Grasses						
Crested wheatgrass	3.9a[1]	.9b	3.9a	1.2b	3.5a	1.3b
Pubescent wheatgrass	1.4a	.5a	1.0a	.5b	1.1a	.7b
Russian wildrye	T a[2]	T a	.3a	.2a	.1a	.1a
Grass total	5.3a	1.4b	5.2a	1.9b	4.7a	2.1b
Forbs						
Ladak alfalfa	.2a	.1a	.3a	.2a	.1a	T b
Grand total	5.5a	1.5b	5.5a	2.1b	4.8a	2.1b

[1]Data pairs within years followed by different letters are significantly different at the 5 percent level.

[2]Trace, less than 0.05/m^2.

Table 3—Comparison of seeded species cover between imprinted and drilled treatments

Species	1982		1983		1984	
	Imprint	Drill	Imprint	Drill	Imprint	Drill
	- - - - - - - - - - - - - - - - - Percent - - - - - - - - - - - - - - - - -					
Grasses						
Crested wheatgrass	0.3a[1]	0.1b	1.7a	0.7b	6.8a	2.9b
Pubescent wheatgrass	.2a	.2a	.8a	.4b	2.4a	2.0a
Russian wildrye	T a[2]	T a	.1a	.1a	.2a	.1a
Grass total	.5a	.3b	2.6a	1.2b	9.4a	5.0b
Forbs						
Ladak alfalfa	T a	T a	.2a	.4a	.5a	.2b
Grand total	.5a	.3b	2.8a	1.6b	9.9a	5.2b

[1]Data pairs within years followed by different letters are significantly different at the 5 percent level.
[2]Trace, less than 0.05/m^2.

Table 4—Comparison of seeded species production between imprinted and drilled treatments

Species	1982		1983		1984	
	Imprint	Drill	Imprint	Drill	Imprint	Drill
	- - - - - - - - - - - - - - - - - Kg/ha - - - - - - - - - - - - - - - - -					
Grasses						
Crested wheatgrass	34a[1]	7b	710a	343b	572a	427a
Pubescent wheatgrass	27a	9b	447a	389b	293a	332a
Russian wildrye	0a	0a	22a	12a	25a	18a
Grass total	61a	16b	1,179a	744b	890a	777a
Forbs						
Ladak alfalfa	3a	3a	70a	64a	54a	16b
Grand total	64a	19b	1,249a	808a	944a	793a

[1]Data pairs within years followed by different letters are significantly different at the 5 percent level.

Production

Trends for herbage production were somewhat different than those for density and for cover (table 4). Production by total seeded grasses, and by crested wheatgrass and pubescent wheatgrass individually, was significantly higher on the imprinted strips in 1982 and 1983. However, by 1984 the production difference had largely disappeared even though the density of seeded grasses was still over twice as high on the imprinted strips (table 2). This was apparently due to compensatory growth resulting in larger individual plants in the less dense stand of the drilled strips. Ladak alfalfa production was significantly greater on the imprinted strips in 1984 but not in 1982 or 1983.

Soil Response

The combination of high winds and light surface soil textures resulted in severe soil loss from the entire study area. Soil depth losses reached 15 to 20 cm in very localized situations. The average loss, however, was much less (table 5). Changes in soil depth included areas of deposition as well as loss and were generally quite variable. Greater soil loss occurred from the drilled strips than from the imprinted strips. Most of the loss occurred the first year. Additional losses the second and third year were relatively minor, and the accumulative losses were not statistically distinguishable from first year's losses. Total soil losses were not significantly different between soil series, although Genola appeared to suffer the greatest loss.

Soil penetrability (index of bulk density) varied between the soil series. Soils of the Genola series were more penetrable than soils of the Shadbliss and Renol series, which may be related to the somewhat greater soil losses from the Genola series (table 5). Greater resistance to penetration in the imprinted strips was still present in 1984—3 years after treatment. This suggests bulk density increases that probably contributed to the initial seedling success may remain for several years after imprinting, particularly if the soil is moist when imprinted.

Table 5—Soil loss by wind erosion, and soil penetrability following wildfire and revegetation treatment

Soil characteristic	Revegetation treatment		
	Imprint	Drill	Average
Soil loss		*cm*	
Shadbliss series	0.8	2.6	1.7a[1]
Genola series	2.6	3.0	2.8a
Renol series	.7	3.2	2.0a
Average	1.4a	2.9b	
Penetrometer reading		*kg/cm²*	
Shadbliss series	2.0	.8	1.4a
Genola series	.5	.4	.4b
Renol series	1.4	0.8	1.1a
Average	1.3a	.7b	

[1]Data within horizonal or vertical sets of averages followed by different letters are significantly different at the 5 percent level.

DISCUSSION

In the Southwest, little benefit was experienced from imprinting where brush control was a necessary effect of the imprinter operation (Cox and others 1986). Creosotebush (*Larrea tridentata*) was not adequately controlled by the action of the imprinter, and established seeded grasses died within 3 to 4 years. This situation was not present in our study because the fire removed all woody plant competition and the area remained free of woody plants during the study. A revegetation study in Oregon resulted in poor establishment of Nordan crested wheatgrass (*Agropyron desertorum*) by imprinting on firm seedbeds where resident herbaceous competition was not removed—unprepared seedbeds or seedbeds prepared by brush beating (Haferkamp and others 1987). When the seedbed preparation was brush beating and disking, which removed the plant competition and loosened the seedbed, the seedling establishment by broadcast seeding and imprinting was comparable to or exceeded seedling establishment by rangeland drilling. Results to date suggest that imprinting as a revegetation technique is most effective when competing plants are not present and when the seedbed is light textured or loose from disking or plowing.

The effectiveness of the land imprinter as a revegetation technique under conditions of this study is obvious, but similar conditions may not often occur. The hot fire that left a clean seedbed and the early fall rains resulted in nearly ideal initial seeding conditions on virtually rock-free soil. However, conditions soon worsened. Although the annual precipitation was 160 to 172 percent of average for the 3 years following seeding, rainfall was only 68 percent of normal during the important April to June period of the first spring (Clary and Wagstaff 1987). Thus, a critical dry period within several years of high rainfall may have reduced initial plant establishment. In addition, light textured soils, high wind conditions, and the low moisture combined to cause unusually severe erosion the first spring to considerable detriment of stand establishment.

Increased plant density with the imprinted treatment likely resulted in part from increased surface soil bulk density and the seed being pressed into close contact with the light-textured soil (Anderson 1981). Observations in other portions of the Little Oak Creek Burn showed greatly improved seedling establishment in crawler tractor tracks on broadcast seeded and chained areas. This is additional circumstantial evidence of the benefit of a compacted seedbed for these soils. The increased soil surface bulk density, in combination with the impressed or embossed surface pattern, apparently resisted eolian soil loss to a greater degree in the imprinted area than the lesser bulk density (greater penetrability) of the rangeland drilled treatment. Loss of more surface soil and, undoubtedly, the accompanying plant seed likely contributed to reduced seedling densities in the drilled areas. A modified rangeland drill with depth bands, chain drags, or press wheels may have resulted in improved plant establishment through better seed coverage and soil compaction.

Treatment costs of $65/ha for imprinting and $42/ha for drilling (Clary and Wagstaff 1987) suggest that, based on 1984 data, a greater density of seeded plants was obtained per dollar spent on imprinting, but more seeded plant forage production was obtained per dollar spent on drilling. Assuming there is a benefit from decreased soil loss, this factor, under our conditions, would weigh in favor of the imprinting technique.

REFERENCES

Anderson, Darwin; Hamilton, Louis P.; Reynolds, Hudson G.; Humphrey, Robert R. 1957 (rev.). Reseeding desert grassland ranges in southern Arizona. Bull. 249. Tucson, AZ: Agricultural Experiment Station. 31 p.

Anderson, R. 1981. Technology for reversing desertification. Rangelands. 3(2): 48-50.

Clary, Warren P.; Wagstaff, Fred J. 1987. Biological and economic effectiveness of several revegetation techniques in the pinyon-juniper-sagebrush zone. In: Everett, Richard L., compiler. Proceedings—pinyon-juniper conference; 1986 January 13-16; Reno, NV. Gen. Tech. Rep. INT-215. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 305-312.

Cox, Jerry R.; Martin-R., Martha H.; Ibarra-F., Fernando A.; Morton, Howard L. 1986. Establishment of range grasses on various seedbeds at creosotebush (*Larrea tridentata*) sites in Arizona, U.S.A., and Chihuahua, Mexico. Journal of Range Management. 39(6): 540-546.

Dixon, R. M.; Simanton, J. R. 1977. A land imprinter for revegetation of barren land areas through infiltration control. In: Proceedings of the 1977 meetings of the Arizona Section of the American Water Resources Association and the Hydrology Section of the Arizona Academy of Science. 1977 April 15-16; Las Vegas, NV. Hydrology and Water Resources in Arizona and the Southwest: 7:79-88.

Dixon, Robert M.; Simanton, J. Rodger. 1980. Land imprinting for better watershed management. In: Proceedings of the symposium on watershed management '80;

1980 July 21-23; Boise, ID. New York: American Society of Civil Engineers: 809-826.
Ganskopp, D. C. 1985. Success of broadcast seeding on untreated, imprinted and chained rangelands. In: 1985 progress report, Research in Rangeland Management. Spec. Rep. 743. Corvallis, OR: Oregon Agricultural Experiment Station: 4-6.
Haferkamp, M. R.; Ganskopp, D. C.; Miller, R. F.; Sneva, F. A. 1987. Drilling versus imprinting for establishing crested wheatgrass in the sagebrush-bunchgrass steppe. Journal of Range Management. 40(6): 524-530.
Heady, Harold F. 1975. Rangeland management. New York: McGraw-Hill. 460 p.
Johnson, Thane J. 1982. Rangeland imprinting in Utah. In: Vegetative rehabilitation and equipment workshop, 36th annual report; 1982 February 4-5; Denver, CO. Missoula, MT; San Dimas, CA: U.S. Department of Agriculture, Forest Service, Equipment Development Center: 16-17.
Plummer, A. Perry; Christensen, Donald R.; Monsen, Stephen B. 1968. Restoring big-game range in Utah. Publ. 68-3. Salt Lake City, UT: Utah Division of Fish and Game. 183 p.
Vallentine, John. 1971. Rangeland development and improvement. Provo, UT: Brigham Young University Press. 545 p.

Clary, Warren P. 1988. Revegetation by land imprinter and rangeland drill. Res. Pap. INT-397. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 6 p.

The land imprinter and rangeland drill were compared for revegetation of a wildfire burn in the Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) vegetation type. Total seeded plant densities and cover were significantly higher with the imprinting treatment. Production of seeded plants was higher on the imprinted area for 2 years; thereafter, production was similar between treatments.

KEYWORDS: rehabilitation, Wyoming big sagebrush, fairway wheatgrass, luna pubescent wheatgrass, Russian wildrye, Ladak alfalfa, wind erosion, range seeding

---

United States
Department of
Agriculture

Forest Service

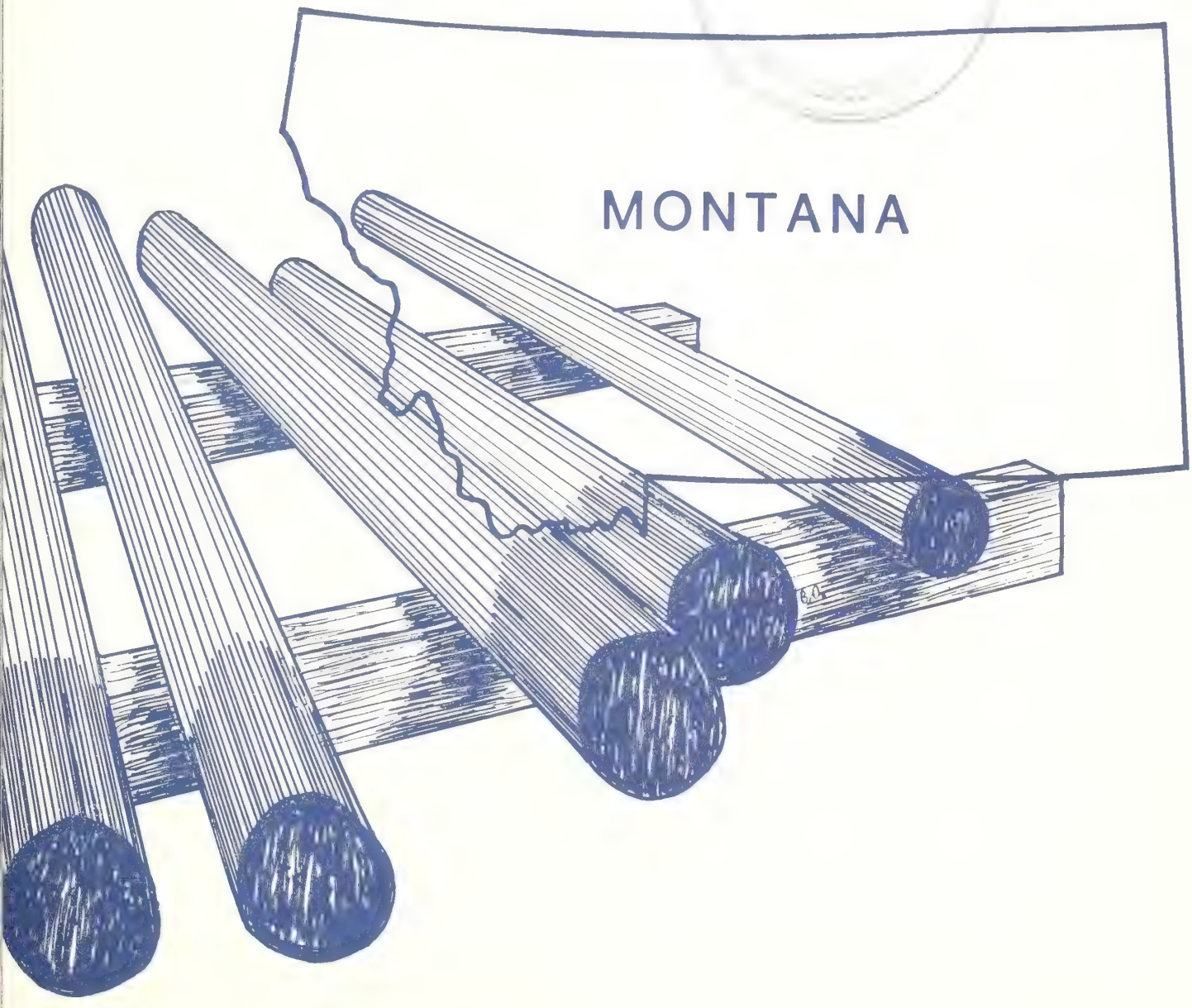
**Intermountain
Research Station**

Research Paper
INT-398

February 1989

Montana's Post and Pole Industry—An Economic Analysis of Production and Markets

David H. Jackson
Kathleen O. Jackson



THE AUTHORS

DAVID H. JACKSON is professor of Forest Economics and Management at the University of Montana, and earned degrees at Ohio University, University of Oregon, and University of Washington.

KATHLEEN O. JACKSON is an independent research contractor and earned degrees at Colorado State University and the University of Oregon.

RESEARCH SUMMARY

Several important dimensions of the Montana post and pole manufacturing industry are presented. While startup costs are reasonably low, the production of products is highly concentrated among a few firms. A key to firm size appears to be the company's apparent success in finding and exploiting out-of-state markets. By comparision with other firms in the solid wood products manufacturing industry, even the large post and pole producers are comparatively small. Only three firms reported that the replacement cost of their capital equipment exceeds $500,000. Because fence posts are the most important product produced, it is not surprising that the economic health of agribusiness is cited as the most important factor affecting demand for post and pole products.

Several regression equations were used to summarize raw material and finished product prices. These can be used to indicate how raw material and product sizes along with other qualitative characteristics influence prices. In addition to statistical models regarding product values, the study concludes that raw material supply and demand are both highly price elastic. Hence quantities purchased and sold are very sensitive to small price changes. These conclusions are based on a variety of models including a model estimating the relationship between capital and labor employed in manufacturing post and pole products as well as a willingness-to-pay questionnaire response.

CONTENTS

Page

Introduction 1
Study Description 1
  Objectives 1
  Data Collection 1
  Problems in Measurement 2
Industry Description 2
  Products Manufactured 2
  Description of Firms 2
  The Degree of Competition 3
  Current Markets and Channels of Distribution 4
  Raw Materials 5
  Firm Size and Its Relationship to Marketing Channels and to Source of Raw Materials 5
  Cross-sectional Analysis of Raw Material and Finished Product Prices 6
  Value Added by Manufacturing 8
Estimating Raw Material Demand 8
  A Primer on Supply and Demand 8
  Price Elasticity of Demand for Materials 9
  Production and Implied Demand for Logs 10
  Raw Material Demand Based on Willingness to Pay 11
  Conclusions Regarding Raw Material Demand 12
Market Supply of Post and Pole Products 12
Conclusions 12
References 13
Appendix A: Demonstration of the Use of Raw Material and Product Price Equations 14
Appendix B: Equipment Summary 14

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Montana's Post and Pole Industry—An Economic Analysis of Production and Markets

David H. Jackson
Kathleen O. Jackson

INTRODUCTION

An economic history of Montana's wood-using industry would show two distinct trends in the supply of raw materials. Over time, an increasing number of native tree species have become commercially significant. Second, corresponding to the expansion of the species utilized, there has been a decrease in the size of trees logged.

In the 1930's, the two species of greatest commercial importance were western white pine (*Pinus monticola*) and ponderosa pine (*Pinus ponderosa*). During that same time, published reports indicate that timber had to be greater than 24 inches in diameter at breast height (d.b.h.) in order to be logged profitably (Baker 1950). Although no parallel estimate of the marginal tree exists for current markets, unpublished data about timber logged in the Northern Rockies are indicative. Figures available from the Northern Region of the Forest Service, U.S. Department of Agriculture, show that the average tree logged on land under its jurisdiction in western Montana and northern Idaho was 17 inches d.b.h. in 1970. By 1984 the average tree size was less than 12 inches d.b.h. for the same geographic area.

Currently, 41 percent of all softwood trees greater than 1 inch d.b.h. on commercial forest land in Montana is lodgepole pine (*Pinus contorta*) and 30 percent is lodgepole 5 inches d.b.h. or less (Green and others 1986). Many land management problems stem from a lack of options for dense, growth-stagnant stands of small-diameter lodgepole pine.

Clearly, the days of a wood products economy based on large-diameter logs are gone. The profitable manufacture of wood products today must entail the use of exceedingly small-diameter timber in order to keep raw materials costs low. In Montana, lodgepole pine is the prevalent small-diameter species available for utilization.

As Benson (1984) indicates, small-diameter lodgepole pine is already being processed in Montana and in the Intermountain West. Lumber and plywood manufacturers are moving toward the use of small logs, while post and pole processors utilize the smallest timber. Stands consisting of 5- to 7-inch d.b.h. size classes are the main candidates for post and pole use. The demand for this kind of raw material is in turn derived primarily from the demand for post and pole products.

Considerable time and effort have been spent studying the lumber, plywood, and pulp and paper sectors. Aside from a basic census of Montana's wood manufacturers (Keegan 1980), there is virtually no information available about post and pole production. The purposes of this study are to compile, describe, and analyze information about the post and pole sector in Montana. Although the primary impetus for this study arose from land management concerns, the findings are pertinent to the performance of Montana's economy. A better understanding of current small-diameter post and pole operations and product markets could be the basis for expanded production. An improved product market would in turn lead to an improved log market and expanded options for using "problem" lodgepole pine stands.

STUDY DESCRIPTION

Objectives

The growing importance of small-diameter lodgepole pine as a source of raw materials warrants an investigation into a sector of the wood products industry that utilizes small logs. In Montana, the principal and virtually exclusive purchasers of small-diameter logs (under 6 inches in diameter) are post and pole producers.

The specific objectives of this study are as follows:

1. Describe the products and level of production for the sector.
2. Characterize the firms comprising the sector.
3. Describe the product markets and distribution channels.
4. Identify the sources of supply for raw materials.
5. Relate the size of the firms to markets and raw materials.
6. Analyze raw material and finished product.
7. Estimate sector demand for raw materials.
8. Determine the costs of production.

Data Collection

The nature of this study and the lack of available information from secondary sources mandated that data should be collected directly from post and pole manufacturers. A list of all known post and pole producers in Montana in 1985 was obtained from the Montana Division of Forestry, Department of State Lands. This list was the basis for establishing the study population.

Attempts were made to contact each of the 43 post and pole operations identified. Of the original list, 17 could not be contacted after repeated attempts or were no longer in business. Two did not produce small-diameter roundwood products. Of the remaining 24, 23 responded positively to a request for information in the form of a telephone survey, while one business declined to provide complete information. Price lists for products and raw materials were obtained from 13 post and pole producers.

The profile of the post and pole industry presented in this study is based on a census of all known producers in the State rather than on a sample. Of the pool of 24 known producers, only three were excluded from the final analysis. Two of this pool provided only partial information. One producer, the Montana State Prison, was considered to be unrepresentative of the larger industry because of the noncompetitive nature of its wage rates and its restricted product market (State agencies). Another producer owned post and pole operations in two locations and combined their production data. Thus, this study represents an 88 percent census of known post and pole producers in spring 1985.

Problems in Measurement

A wide variety of post and pole products are manufactured in Montana, which results in a broad range of product prices. Products are not only diverse but lack uniformity in size. This complicated the measurement of production activities.

Manufacturers reported production in terms of the number of pieces produced. There are no published volume tables available for small roundwood lodgepole pine logs by piece. As the study progressed, it became increasingly apparent that the reporting and analysis of production data would be facilitated by converting to cubic-foot volume estimates. Volume estimates are more familiar to people outside the post and pole business and are more comparable to production data in other sectors of the larger wood-processing industry.

Cubic-foot estimates of the small-diameter products entailed the application of a taper factor of $^{5}/_{8}$ inch per 8-foot length of raw material to the piece data supplied by post and pole producers. In addition to the number of pieces, average small-end diameter and length data were obtained. The taper factor or value was used to predict large-end diameter, and then cubic-foot volume estimates were calculated based on length and average diameter. No allowances were made for peeling, drilling, capping, or pointing of materials.

The diversity of product sizes is no doubt related to the shape and form of the trees utilized in manufacturing post and pole products. Although the lack of cubic volume estimates is a problem from a research perspective, it is of little importance to producers and buyers. For instance, purchasers of fenceposts most likely buy posts of a certain diameter and length rather than on the basis of cubic volume. The number of pieces of a particular size is far more important than the volume of wood.

INDUSTRY DESCRIPTION

Products Manufactured

Firms classified as part of the post and pole processing sector manufacture a variety of roundwood products. Fenceposts not only vary in diameter and length, but in treatment with preservative, that is fully, partially, or butt-treated or untreated. In addition, fenceposts may be peeled or unpeeled, pointed or unpointed. Posts produced for decorative purposes are drilled for rails; the number of holes depends on the number of fence rails to be supported. Jackleg fenceposts are manufactured so that pairs stand above ground in a crossed position. These fences are most often used where rocky soil conditions preclude the digging of post holes or the driving of fenceposts.

Rails are available in treated or untreated form and may be peeled or unpeeled. Those manufactured for use as decorative fencing have doweled ends to fit holes bored in the post. Gates are available either assembled or unassembled. Haystack panels and portable corrals are manufactured by a few post and pole yards, as are barn poles, tree props, and grape stakes.

In addition to roundwood production, some post and pole firms operate small sawmills. Although data on lumber production were not included in this study, it is of note that this minor degree of integration within the wood products industry has taken place in the post and pole sector.

The prices for the products manufactured by the post and pole industry reflect both the degree of processing and raw material costs. As in the case of production volume, the diversity of product prices necessitated the development of a standardized price measure rather than the use of prices reported directly by manufacturers. Thus, a set of price equations were developed that related price to size and volume as a means of reporting raw material and product prices.

Description of Firms

Montana's post and pole sector is geographically dispersed in 17 counties on both sides of the Continental Divide. Post and pole firms range in size from small, part-time operations employing less than one person on an annual basis to larger scale plants with an average annual employment of 45 people. Overall, the sector is characterized by relatively small employment, with only two firms employing 20 or more employees and 13 employing six or fewer employees. The average annual employment (including full and part time) is seven.

The payrolls of post and pole producers ranged from $6,000 to $500,000, with an average payroll of $90,500. Reflective of the small number of employees, 13 of the producers had payrolls less than $50,000. A summary of employment and payroll information is provided in table 1.

Table 1—Employment and payroll summary—Montana post and pole sector (one firm unreported)

Employees	Firms	Payroll	Firms
0 - 3	13	$ 6,000 - $10,000	3
4 - 6	5	11,000 - 20,000	2
7 - 10	1	21,000 - 30,000	5
11 - 20	0	31,000 - 50,000	3
20 +	2	51,000 - 199,000	4
		200,000 +	3
Total	21		20

Table 2—Volume estimates of small-diameter roundwood products—Montana post and pole sector

Product	Volume	Total production
	Ft^3	Percent
Posts	1,709,948	55.6
Poles	359,305	11.7
Utility poles	41,638	1.4
Barn poles	118,860	3.9
Rails	487,022	15.8
Props	255,965	8.3
Decorative fencing	101,049	3.3
Total	3,073,787	100.0

Information about the capital stock of the post and pole sector was obtained from producers who were asked to estimate the replacement value of plant and equipment, including vehicles. The results were:

Estimated value	Number of firms
$ 0 - 20,000	4
21,000 - 60,000	4
61,000 - 100,000	4
101,000 - 250,000	3
251,000 - 500,000	3
501,000 +	3
Total	21

The value of the capital stock for more than half of the industry is less than $100,000.

Levels of production were calculated by converting numbers of pieces for each product into estimates of cubic-foot volume (see Problems in Measurement). The seven major products are shown in table 2.

Posts—the only product manufactured by all firms—accounted for the largest volume of production. Only two firms produced utility poles and barn poles, eight made decorative fencing, 16 manufactured rails, and 17 made other kinds of poles.

The Degree of Competition

Manufacturing may be characterized according to the degree of competition present in the industry. A competitive industry is one in which the level of production of any one firm will exert a negligible influence on the prices of products sold or on the unit costs of raw materials and other factors of production purchased. In contrast, a monopolistic industry represents a form of "price-seeking" behavior. A monopolistic firm is able to govern its production as a means of influencing the price of the products it manufactures and sells. Likewise, firms that can influence the price paid for raw materials and other factors of production are called monopsonists.

Competition and monopoly are extremes and are useful in describing industrial organization. But most manufacturing in the United States is neither purely competitive nor purely monopolistic. The degree of competition represents a more realistic way of classifying an industry or sector. In determining the degree of competition, several factors are usually evaluated. Are there barriers limiting new entrants to the industry such as large capital requirements or legal limitations such as patents or licenses? Are there close substitutes for the products? Are there particular brands that evoke consumer loyalties? Finally, is production dominated by a few firms?

By these criteria, it appears as though post and pole manufacturing in Montana is highly competitive, although not all of the indicators point in this direction. Rapid turnover of firms is indicated by the number of firms no longer in business or that could not be reached by telephone at the time of the survey. In addition, little capital is required to enter the post and pole business. Only three of 21 firms reported the replacement value of their capital stock to be in excess of $500,000, while four estimated the replacement value of their capital stock as less than $6,000.

The presence of substitute products indicates a competitive industry. As shown in table 3, fenceposts are the most important roundwood product of the post and pole sector. Obvious substitutes are metal posts. Barbed wire and woven fence are replacements for wooden rails, and lumber and metal products may be substituted for roundwood panels, gates, and so on. There is little evidence of brand preference for these goods, which suggests that the post and pole sector is competative.

Domination of an industry by a few firms suggests something less than perfect competition. Figure 1 illustrates that the Montana post and pole industry is highly concentrated. The straight line represents a theoretical distribution of production if all firms were equal in size. The curved line plots actual distribution of production. The distance between the two lines indicates the relative degree of concentration of ownership. Thus, the graph shows that 60 percent of post and pole producers are responsible for only 20 percent of total volume produced in the State. Ninety percent of producers account for only two-thirds of production, leaving 10 percent (two firms) responsible for more than one-third of total volume. These two firms are as dominant in the post and pole sector as their counterparts, Champion and Plum Creek, in the lumber and plywood sectors of the State.

Although Montana's post and pole production is concentrated, the product market is not confined to the State. Manufacturers in Montana face competitors throughout

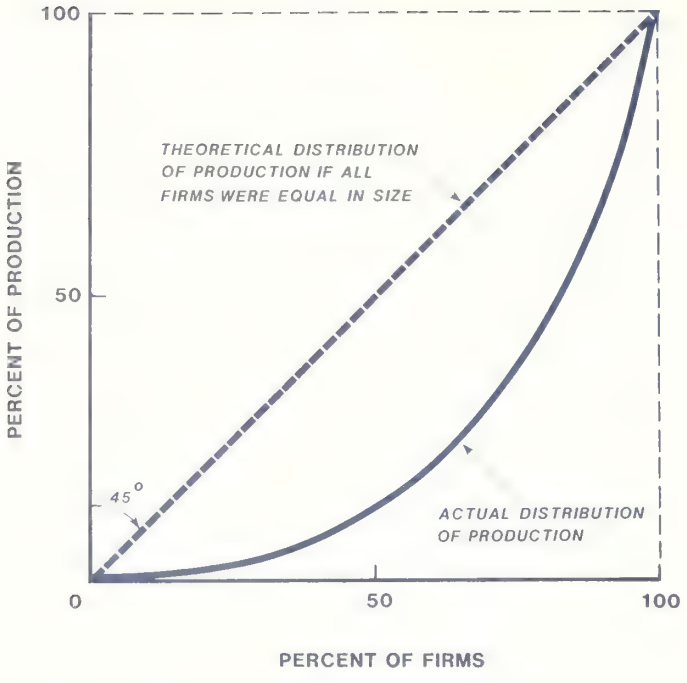


Figure 1—Concentration of manufacturing of posts and poles in Montana.

the West. An unknown quantity of posts and poles are imported into the State. Thus, while production within the State may be concentrated, a competitive market prevails within the larger post and pole sector. Further, there is evidence to suggest that Montana's producers participate in that larger market.

Current Markets and Channels of Distribution

The survey revealed the geographic distribution of markets for Montana's post and pole producers. All except one firm reported sales within the State. As shown in table 3, 43.5 percent of the total volume of products was sold in Montana. The California/Nevada market was the second largest (19.6 percent), followed by Wyoming/Colorado and Dakotas/Nebraska (13.2 percent each).

Firms were also asked to identify customers as end user, wholesale distributor, or retail outlet. As shown in table 4, wholesalers purchased 43.5 percent; end users 34.5 percent; and retail outlets 21.1 percent of total volume produced.

Market demand was assessed by the responses of producers to a list of factors that might affect product sales. Producers were asked to assess the importance of each item. Items were weighted according to importance. Market demand is affected by:

Item	Score[1]
Economic health of agribusiness	35
Geographic location of plant	22
Freight rates	19
Highway and public works	18
Housing construction	13
Advertising	11
Competition with foreign markets	1
Availability of export markets	1

The weighted scores indicate that the economic health of agribusiness is the most important influence on roundwood product sales. The geographic location of the business, freight rates, and highway/public works construction were of about equal importance to producers.

Table 3—Destination of shipments from Montana post and pole producers

Geographic area	Volume	Total production
	Ft^3	*Percent*
Montana	1,335,576	43.5
Pacific Northwest	16,339	.5
California/Nevada	602,016	19.6
Wyoming/Colorado	414,384	13.5
Arizona/New Mexico	20,526	.7
Dakotas/Nebraska	405,181	13.2
Midwest	27,612	.9
Oklahoma/Texas	79,248	2.6
Canada	50,538	1.6
Other/unknown	122,367	3.9
Total	3,073,787	100.0

Table 4—Purchasers of roundwood products

Type of purchaser	Volume	Total production
	Ft^3	*Percent*
Wholesale	1,335,956	43.5
End user	1,059,782	34.5
Retailer	648,305	21.1
Other/unknown	29,744	.9
Total	3,073,787	100.0

[1]Scores represent summary of responses weighted by (2) for a great deal of importance, (1) for some importance, and (0) for no importance.

Raw Materials

The firms surveyed were asked to indicate the source of raw materials and volumes purchased. Sources included the Forest Service, the State of Montana, private owners, and other public land agencies.

Table 5 shows that the Forest Service and privately owned lands supplied two-thirds of the raw materials. Most firms bought from both private and Forest Service sources, but five firms were solely reliant on one or the other.

Producers were asked if they had problems acquiring raw materials within the last 5 years. Out of 20 firms surveyed, 12 (60 percent) reported some difficulty. Nine of those firms expressing problems obtained 50 percent or more of their raw material from Forest Service lands.

The problem most frequently cited was difficulty in finding people willing to cut and deliver materials at competitive prices. Unavailability of timber and red tape were mentioned by more than half of the manufacturers.

Firm Size and Its Relationship to Marketing Channels and to Source of Raw Materials

Our study examined the relationship of firm size, source of raw materials, and marketing channels. For purposes of this analysis, the post and pole producers were divided into quartiles based on size, with cutoff points determined by production volume.

Data on sales of products are presented in table 6. These data show dramatic differences in geographic markets between the large and small firms. Thus, while 47 percent of the total volume of all sales takes place within Montana, only 25 percent of the volume of large producers is marketed in-State. Small producers sell almost exclusively to Montana purchasers.

Category of purchasers was also related to firm size, using the same quartiles. The results displayed in table 7 suggest that the smaller firms sell to end users to a considerably greater extent than do the five largest producers

Table 5—Source of raw materials

Owner	Volume	Total production
	Ft[3]	*Percent*
Forest Service	1,087,609	35.4
Private	959,341	31.2
Other public	899,401	29.3
State	127,436	4.1
Total	3,073,787	100.0

Table 6—Geographic markets by firm size

	Product destination[1]			
	Inside Montana		Outside Montana	
Firm size[2] (quartiles)	Volume	Percent Q-sales	Volume	Percent Q-sales
Top	481,823	(25)	1,348,948	(75)
Second	522,864	(69)	233,536	(31)
Third	357,774	(93)	46,707	(7)
Fourth	73,116	(94)	5,062	(6)
Subtotal	1,435,577		1,634,253	
Percent total	(47)		(53)	
Total	3,069,830			

[1]Only known product destinations included.
[2]Based on total cubic foot volume produced as follows: top (>200,000), second (200,000-100,000), third (99,000-45,000), fourth (<45,000).

Table 7—Channels of product distribution by firm size

	Purchaser[1]					
	End user		Wholesaler		Retailer	
Firm size (quartiles)	Volume	Percent Q-sales	Volume	Percent Q-sales	Volume	Percent Q-sales
Top	298,951	(16)	1,229,253	(64)	384,729	(20)
Second	468,301	(61)	61,662	(8)	236,897	(31)
Third	241,030	(84)	45,041	(16)	0	(0)
Fourth	51,500	(66)	0	(0)	26,679	(34)
Subtotal	1,059,782		1,335,956		648,305	
Percent total	(35)		(44)		(21)	
Total			3,044,043			

[1]Only known purchasers included in table.

Table 8—Source of raw materials by firm size

Firm size (quartiles)	Ownership category[1]					
	Forest Service		Private		Other public	
	Volume	Percent Q-total	Volume	Percent Q-total	Volume	Percent Q-total
Top	229,895	(12)	769,292	(40)	907,156	(48)
Second	601,110	(78)	128,702	(17)	37,048	(5)
Third	207,199	(69)	32,573	(11)	62,074	(21)
Fourth	49,405	(63)	28,774	(37)	0	(0)
Subtotal	1,087,609		959,341		1,006,278	
Percent total	(36)		(31)		(33)	
Total			3,053,228			

[1]Only known sources included in table.

of posts and poles. Two-thirds of the volume of the largest five producers is sold to wholesale distributors. Overall, sales to retail outlets constitute the smallest volume of sales for all groups of producers.

Finally, firm size was compared to sources of raw materials. As shown in table 8, while the Forest Service provides one-third of all raw materials, the five largest producers are far less reliant on this source than are the smaller producers.

Cross-sectional Analysis of Raw Materials and Finished Product Prices

The diverse sizes and prices of finished products made it difficult to summarize such data. Ideally, prices should be tied to a volume measurement of wood, such as cubic feet. But all post and pole yards buy raw materials from cutters based on measurement of small-end diameter of each piece. The same is true for product prices. Manufacturers sell posts, poles, and rails of various lengths and small-end diameters, with no standard system of size classes or prices.

In order to aggregate prices for raw materials and finished products, we developed an equation that incorporates diameter and length. Regression analysis was used to obtain summary coefficients for raw material prices as a function of diameter squared (D^2) times length (L). Equations 1, 2, and 3 represent price estimates for three length classes of raw materials delivered to the yards of the manufacturers.

Thirteen producers complied with our request to furnish current price lists for both raw materials and products. From these lists, 134 raw material prices were obtained. Small-end diameters included on the raw material or "cutters" price lists ranged from 2 to 7.5 inches. Lengths ranged from 5.33 to 30.5 feet.

Equation 1 represents a regression model that predicts the unit price (price per piece) for short lengths of delivered roundwood (5.33 to 10 feet). These lengths are generally associated with fenceposts, tree props, or grape stakes. Equations 2 and 3 are regression models where the coefficients represent price estimates for the medium-length and long-length classes of raw materials.

Segmenting reported prices into three length classes resulted in better explanatory equations than would have been the case with ungrouped data. Specification of independent variables was identical for the three size classes. Each equation uses a curvilinear measure, the exponential of length in feet, which indicates that price per piece increases at a decreasing rate for longer lengths. A "volume" type variable, D^2L, using small-end diameter (D) measured in inches multiplied by length (L) measured in feet, serves as a proxy for cubic volume.

Estimates for product prices were determined using a similar method. The 13 firms that submitted prices for products are again the foundations for the post, pole, and rail price equations.

Equation 1. Price Equation for Short-length Raw Materials—

$$P_1 = 0.1799 + 0.0027\,D^2L + 1.16210e.05\,e^L \qquad (1)$$

$n = 62$

Adjusted $R^2 = 0.839$ $\qquad F(2/59) = 159.693$

Standard Error as a percentage of mean Y (unit price) = 19.39 percent

where:

P_1 = price for lengths 5.33 through 10.0 feet

D = diameter in inches

L = length in feet

e = exponential function.

Equation 2. Price Equation for Mid-length Raw Materials—

$$P_2 = 0.3604 + 0.0039\,D^2L + 1.59146e.08\,e^L \qquad (2)$$

$n = 48$

Adjusted $R^2 = 0.944$ $\qquad F(2/45) = 398.785$

Standard Error as a percentage of mean Y (unit price) = 14.54 percent

where:

P_2 = price for lengths 10.1 through 18.0 feet.

Equation 3. Price Equation for Long-length Raw Materials—

$$P_3 = 0.7943 + 0.0056\,D^2L + 1.30432e.13\,e^L \quad (3)$$

$n = 24$

Adjusted $R^2 = 0.863$ $F(2/21) = 79.693$

Standard Error as a percentage of mean Y (unit price) = 79.69 percent

where:

P_3 = price for lengths 18.1 through 30.5 feet.

There were more than 1,000 observed prices indicative of the size, length, treatment, and other processing (peeling, pointing, drilling, doweling). A systematic 10 percent sample of the post, pole, and rail prices, FOB producer's yard, was taken from these price lists and used as data for deriving the regression coefficients.

Equation 4 presents the model for post prices. Due to basic size similarities, other products like grape stakes are included in the data used for this equation. The upper length for posts included was arbitrarily set at 10 feet. The D^2L variable represents the same volume type measure utilized in the raw material price equations.

Equation 4. Price Equation for Post Lengths Under 10 Feet—

$$P_4 = 0.1099 + 0.9643\,H + 0.0128\,D^2L + 0.1165\,SAT \quad (4)$$

$n = 41$

Adjusted $R^2 = 0.834$ $F(3/37) = 67.741$

Standard Error as a percentage of mean Y (unit price) = 23.31 percent

where:

P_4 = price for lengths under 10 feet

H = drilled, yes = 1; no = 0

D = diameter in inches

L = length in feet

SAT = surface area treated.

Because some posts are fully treated and others are butt-treated, it was assumed that the product price would reflect the surface area treated. A proxy for surface area was estimated using the small-end diameter in inches, the length (L) of the piece in feet actually treated, and the constant, π, so that: $SAT = \pi/12\,DL$.

The other variable in the price equation for posts, drilled (H), is a dummy variable where a value of 1 was assigned if the post had holes drilled in it for doweled rails. The sample included both two- and three-hole posts. Other variables for pointed/unpointed and peeled/unpeeled characteristics were not statistically significant and were eliminated from the final equation.

Equations 5 and 6 represent the models for short and long poles. Short poles ranged from 10.1 through 16 feet in length. Long poles ranged from 16.1 to 30.5 feet. The variables in the two pole equations are defined as in equation 4.

Equation 5. Price Equation for Short Poles—

$$P_5 = 0.5836 + 0.0177\,D^2L + 0.2328\,SAT \quad (5)$$

$n = 31$

Adjusted $R^2 = 0.913$ $F(2/28) = 146.504$

Standard Error as a percentage of mean Y (unit price) = 24.86 percent

where:

P_5 = price for poles 10.1 through 16.0 feet.

Equation 6. Price Equation for Long Poles—

$$P_6 = -0.0942 + 0.0170\,D^2L + 0.2034\,SAT \quad (6)$$

$n = 14$

Adjusted $R^2 = 0.780$ $F(2/11) = 24.097$

Standard Error as a percentage of mean Y (unit price) = 23.43 percent

where:

P_6 = price for poles 16.1 through 30.5 feet.

Equation 7 is the estimated price equation for rails. Rails were defined as reported on producers' price lists. They are similar in length to posts and poles (as small as 8 feet in length, but may be as large as 20 feet in length). Some rails are treated and others are not. Some are doweled on the ends, although doweling usually increases the price of a rail by less than $0.50 and was not a significant variable.

Equation 7. Price Equation for Rails—

$$P_7 = -0.0942 + 0.0170\,D^2L + 0.1797\,SAT \quad (7)$$

$n = 22$

Adjusted $R^2 = 0.801$ $F(2/19) = 43.361$

Standard Error as a percentage of mean Y (unit price) = 37.08 percent

where:

P_7 = price for rails.

The final statistical price model was developed for wooden gates. Manufacturers offered a variety of gates, with optional lengths, number of rails, and peeled or unpeeled rails. Gate lengths ranged from 4 to 16 feet and the number of rails from two to six. Equation 8 is based on 46 price-product observations from six producers.

Equation 8. Price Equation for Gates (Unassembled)—

$$P_8 = -0.1198 + 2.4297\,L + 1.2630\,R - 1.7824\,P - 0.4774\,L{*}P + 2.6043\,R{*}P \quad (8)$$

$n = 47$

Adjusted $R^2 = 0.898$ $F(5/41) = 81.787$

Standard Error as a percentage of mean Y (unit price) = 9.04 percent

where:

P_8 = price of gates

L = length

R = number of rails

P = peeled, yes = 1; no = 0

$L{*}P$ = length times peeled

$R{*}P$ = number of rails times peeled

Table 9—Value added by manufacturing

Product	Volume	Purchase price		Product price		Value added	
		Per unit	Per cubic foot	Per unit	Per cubic foot	Per unit	Per cubic foot
	Ft^3	Dollars					
6.5-foot by 4-inch-top fencepost, 3-foot treated, no holes	0.64	0.47	0.73	1.80	2.81	1.33	1.48
12-foot by 3-inch-top rail untreated	.78	1.06	1.36	2.35	3.01	1.29	1.65
15-foot by 6-inch-top pole untreated	3.55	2.52	.71	8.97	2.53	6.45	1.82
15-foot by 6-inch-top pole full treatment	3.55	2.52	.71	14.46	4.07	11.94	3.36

Miscellaneous post and pole products and their average prices, computed directly from price lists supplied by manufacturers, are summarized as follows:

Product	Unit price
Peeled jackleg posts (doweled and drilled)	$ 3.57
Unpeeled jackleg posts (doweled and drilled)	2.39
Haystack panels (16-foot lengths)	15.50
Portable corrals (12 and 16 feet, peeled and unpeeled)	24.75

Value Added by Manufacturing

The equations developed for raw material prices and for the sale price of products, FOB producer's yard, can now be used to estimate value added by manufacturing beyond the cost of raw materials. Table 9 gives examples for selected products, while appendix A demonstrates how the equations were used to obtain the prices.

Using the fencepost as a standard product (6.5-foot length, 4-inch top), the producer pays about $0.47 per post for raw material delivered to the yard, or $0.73 per cubic foot. After peeling, pointing, capping, and treating a 3-foot butt portion, the post is sold for $1.80 at the yard or about $2.81 per cubic foot. Value added in manufacturing for capital, labor, and preservatives is $1.33 per unit, or about $1.48 per cubic foot. The other entries in the table are self explanatory.

The main factor affecting value added per cubic foot is the application of preservatives. Most post and pole manufacturers specify the delivery of green lodgepole logs. This may reduce preservative costs because dry wood absorbs more preservative than green wood. Also, application of a preservative such as pentachlorophenol requires vats of various lengths as well as additional amounts of labor and production time.

ESTIMATING RAW MATERIAL DEMAND

A Primer on Supply and Demand

This section describes the demand for small-diameter logs used to manufacture post and pole products. Because allocation of resources in a market economy centers around the concepts of supply and demand, a brief review of economic principles may be helpful.

In general, demand for a resource is characterized by: (1) an inverse relationship between the price of a resource and the quantity that will be purchased, and (2) shifts in the demand function due to changes in variables such as the price of goods related to the consumption or use of the resource or the purchasing power of consumers. These two aspects of demand are shown in figure 2. Demand curve D1 and movement along this function or schedule demonstrates the inverse relationship between price and quantity. The demand function D2 demonstrates how a demand function can shift from its original (D1) location in response to changes related to the consumption or use of the resource.

The supply of goods in the marketplace is usually thought of as the aggregate of the goods produced and offered for sale. Supply is related to both product price and the costs of factors of production. Notice in figure 3 that the supply (S1) of goods is an increasing function of product price. Shifts in the supply function demonstrated by (S2) reflect changes in unit costs of production inputs such as wage rates or raw material costs.

The price or value of goods in the marketplace is thought of as the simultaneous result of supply and demand forces. Thus, combining the graphs of figures 2 and 3, price P_e will result at equilibrium quantity Q_e when the demand function D1 and the supply function S2 intersect as shown in figure 4.

If demand for a product is to be estimated, a basic question is how responsive is quantity demanded to a small change in price? It would appear that this question can be answered by inspecting the slope of the demand function. But the slope of a demand function can be misleading because it depends on the scaling used in measurements. For example, if one measured the quantity demanded for timber in the United States in terms of billion board feet, and defined the price in dollars per thousand board feet, the slope of the demand curve would be different than the case where the analyst defined the quantity in terms of **million** board feet and the price in dollars per **thousand** board feet.

As a result of measurement enigmas, economists have developed the idea of elasticity to measure responsiveness. The price elasticity of demand is defined as the

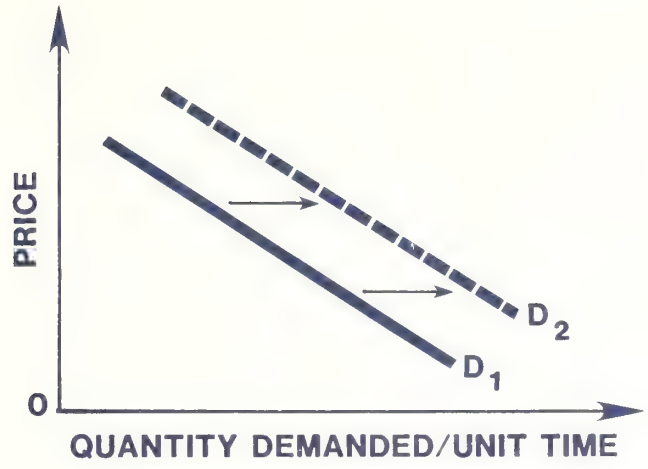


Figure 2—Typical demand function and demand shift.

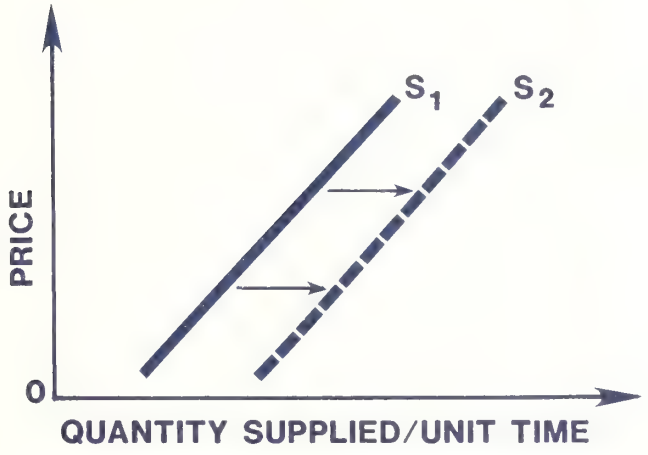


Figure 3—Typical supply function and supply shift.

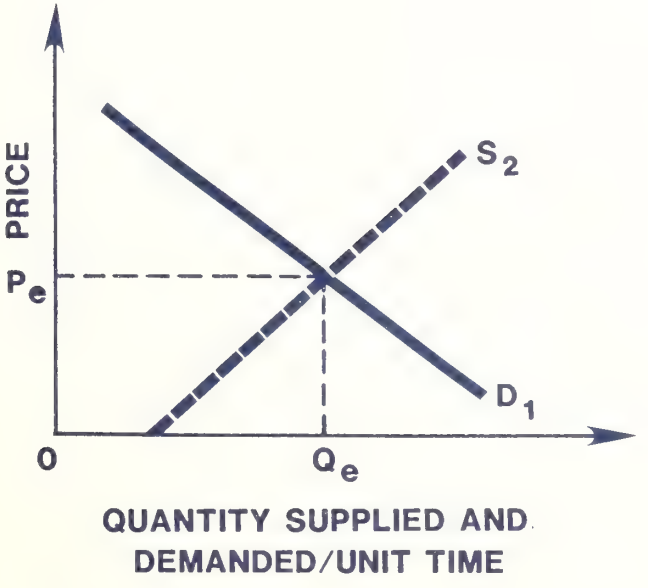


Figure 4—Price determination.

percentage change in quantity demanded which corresponds to a small percentage change in the price of the goods. Unlike the slope of a demand function, elasticity is unitless and scale adjusted.

Just as there is a price elasticity of demand, there is also a price elasticity of supply. In addition, elasticities can also be estimated for the variables that shift the supply and demand functions. Estimates of elasticity tell analysts a good deal about the nature of the market for resources. Recalling that the price elasticity of demand is the percentage change in quantity divided by the percentage change in price, demand is said to be price elastic if the absolute value of the percentage quantity change exceeds the absolute value of the percentage price change. Conversely, demand is price inelastic if the percent quantity change is less than the percentage price change, again in terms of absolute values. The idea of elasticity is applied to any number of economic variables and phenomena, but of importance here is the point that elastic demand is more price responsive than inelastic demand.

Price Elasticity of Demand for Materials

Two alternative approaches were used to estimate the price elasticity of demand for small-diameter logs in the post and pole sector. First, the underlying production relationships that shape the supply function illustrated in figure 3 were studied. Basic to this approach is an understanding of the relationship between capital and labor employed in the manufacturing of post and pole products. Data obtained from producers resulted in the estimation of a production function for the post and pole sector. In turn, this production function allows inferences to be made about the demand for raw materials used in the manufacturing process.

An alternative and somewhat less conventional approach was used to estimate the price elasticity of demand for small-diameter logs. This entailed an analysis of responses to questions about production decisions given changes in raw material prices. As will be shown, the two approaches to demand estimation, while producing somewhat different estimates of elasticity, provide mutually reinforcing information.

Production and Implied Demand for Logs

The production function approach to demand estimation for logs involves three steps. First, a production function that estimates the numerical relationships between inputs utilized and the level of output produced is estimated. Second, the results of this production function are used to make inferences about the total cost and marginal cost functions. Finally, from the marginal cost function, conclusions are drawn about the price elasticity of the derived demand for small logs.

In equation form a production function might be commonly stated as follows:

$Q = f(K, L, N)$

where:

Q = quantity of posts and poles produced

K = amount of capital

L = amount of labor

N = amount of raw materials.

The methodological problem apparent with post and pole manufacturing is the overwhelming relationship between Q, the physical measure of output, and N, the measure of raw material input. As a result of the overwhelming relationship between Q and N, an alternative specification of the production function, where N is left out, is presented. The revised function is as follows:

$Q = f(K, L)$

As in all production studies, the measurement of capital, K, can be elusive (Walters 1963). The questionnaire evoked responses for the technical production capacity of each product per 8-hour shift. These capacity figures were converted to annual capacities by assuming 50 producing weeks per year. Then a ratio of actual annual production to capacity was multiplied by the reported capital stock value and was used to measure capital utilization. Labor was measured by the average annual number of employees reported by producers. Natural logarithins of all the variables were taken to linearize the model so that simple linear regression analysis would be used to estimate model coefficients.

Equation 9. Production Function—

$$\ln Q = 10.13 + 1.09 \ln K + 0.01 \ln L \qquad (9)$$

$n = 19$

Adjusted $R^2 = 0.768$ $F(2/16) = 27.023$

Standard Error as a percentage of mean Y (total ln cubic feet) = 5.89 percent

Taking antilogs of the above model, it can be reexpressed as:

Equation 10. Production Function—

$$Q = 10.13 K^{1.09} L^{0.01} \qquad (10)$$

The sum of the exponents in equation 10 has an important economic meaning. Where their sum is greater than 1, increasing returns to scale between inputs and outputs are inferred (Silberberg 1978). The idea of increasing returns is not consistent with a stable industry equilibrium and cannot lead to meaningful logical propositions. In addition, labor, as specified, is not a significant variable and is correlated with capital ($R = 0.51$).

An alternative production function, using the original Cobb-Douglas model where the exponents are restricted to a sum of 1, was estimated for the data. This restricted model is consistent with constant scale economies. The Cobb-Douglas function is presented as equation 11.

Equation 11. Cobb-Douglas Production Function—

$$\ln Q = 10.17 + 0.979 \ln (L/K) \qquad (11)$$

$n = 19$

Adjusted $R^2 = 0.940$ $F(1/17) = 249.910$

Standard Error as a percentage of mean Y(ln cubic feet produced/K) = 35.66 percent

The restricted model appears to fit the data better than the first model. The potential multicollinearity between K and L is eliminated and the overall F level improves substantially. A statistical test was conducted to determine whether differences in the two models were significant (Koutsoyiannis 1977). It was found that the hypothesis of no difference could not be rejected so the restricted production function model was chosen.

By rearranging variables and taking antilogarithms, the statistically estimated post and pole production function is:

Equation 12. Post and Pole Production Function—

$$Q = 10.17 K^{0.979} L^{0.021} \qquad (12)$$

To summarize, there is both a fixed quantitative relationship between the use of small-diameter logs and the production level and constant returns to scale over the observable levels of production. It is now possible to focus the analysis on production costs.

It is well known in economics that constant returns to scale produce a linear total cost function (TC) such as depicted in figure 5a. That is, the total cost of manufacturing post and pole products rises at a constant rate holding the unit costs of capital, labor, and raw materials constant. The rate of change of the total cost function, or more specifically, the change in total costs with respect to a change in the level of production is termed marginal cost (MC).

Because the total cost (TC) rises at a constant rate, marginal cost (MC) will be a constant (horizontal line), as is shown in figure 5b. Under conditions where the unit prices of capital, labor, and logs are constant and the number of producers and the technological state of the arts are unchanged, the MC function is synonymous with the aggregate supply function. Thus, the horizontal supply function is perfectly elastic with respect to product price.

Determining the price elasticity of demand for factors produced in fixed proportions with the level of output dates back to Marshall (Friedman 1976). The principles are demonstrated graphically in figures 6a and 6b. In figure 6a, post and pole price is held constant at a level of A, and the marginal cost of producing these products less raw materials costs ($MC_{K,L}$) is shown at level B. The derived demand for raw materials is the product demand less the marginal costs of production excluding log costs of A minus B. Given that demand and $MC_{K,L}$ are both horizontal functions, the derived demand for logs will also be horizontal, as indicated in figure 6b.

The conclusion drawn from the production function approach is that the price elasticity of demand for small-diameter logs used in the manufacturing of post and pole products is perfectly elastic or price responsive.

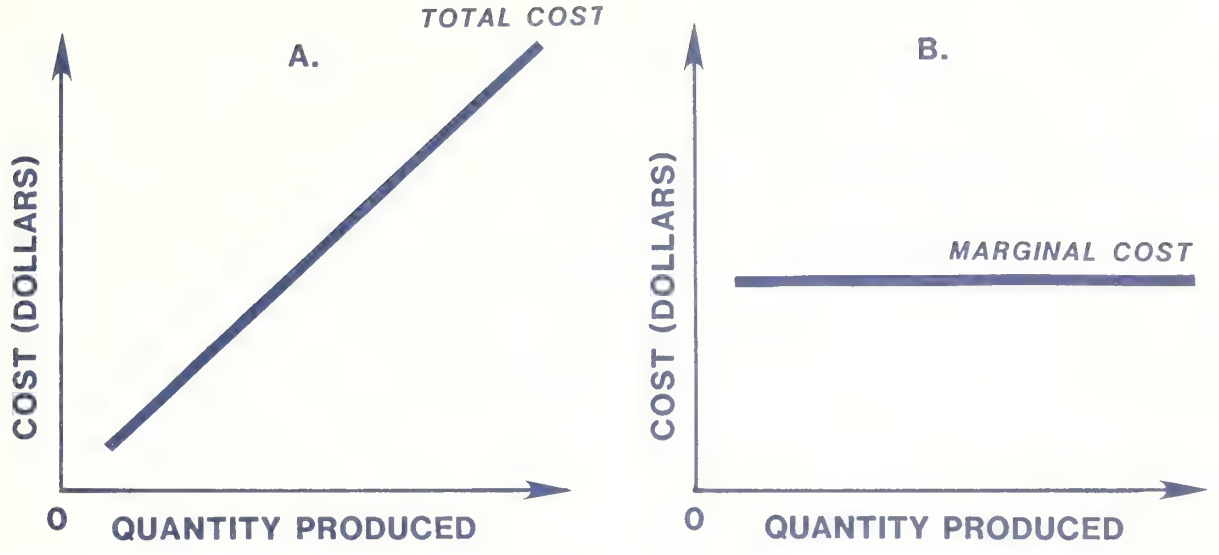


Figure 5—(a) Total cost function, (b) marginal cost function.

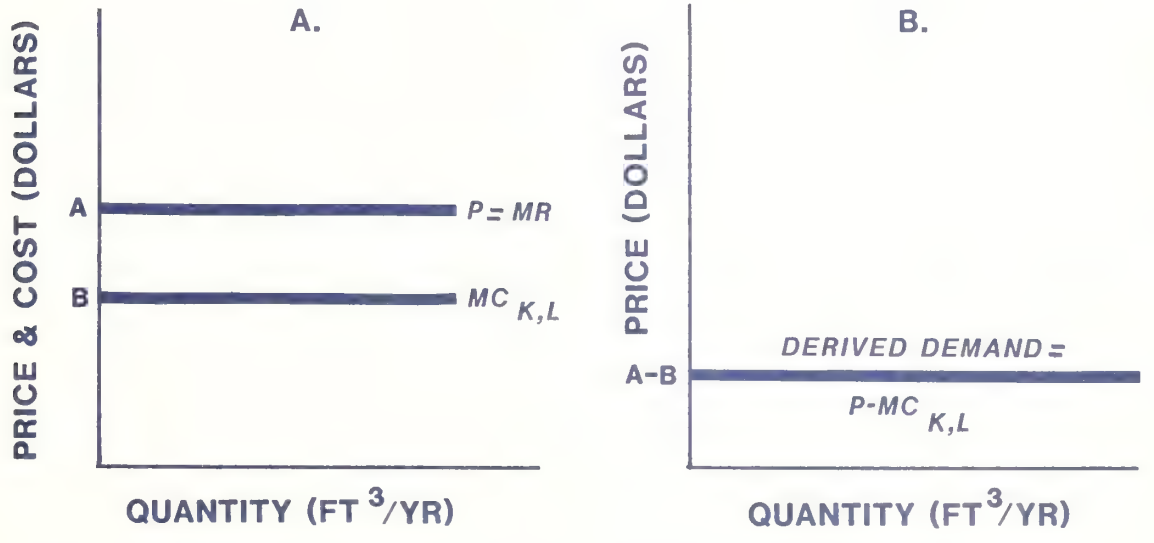


Figure 6—Product demand, marginal costs of production, and short-run derived demand for raw materials where the quantitative relationship between raw material input and product output is fixed.

Raw Material Demand Based on Willingness to Pay

A second approach to estimating the price elasticity of demand for raw materials involved use of data from the survey. During the interviews, each respondent was asked how production would change if there was a 10 percent increase in raw material prices. Given the fixed relationship between raw material inputs and production outputs, the results of this question were used to develop an alternative estimate of the derived demand for raw materials.

Responses were given by product and were aggregated for the firms included in the study. Overall, the response to a 10 percent increase in raw material prices (assuming product prices and employee wages did not change) was a 15.19 percent decrease in output. It is inferred that there would be an equal decrease in the purchase of raw materials. Thus, using the willingness-to-pay approach, the predicted price elasticity of demand for raw materials is –1.52.

Conclusions Regarding Raw Material Demand

The estimate of price elasticity based on the production function approach and the estimate based on producer willingness to pay both suggest that demand is price elastic. The question may arise as to why the measures of elasticity have such a broad range. It appears that during

the year the post and pole sector was studied, firms were operating far below their productive capacity. An estimate of capital utilization based on questions about the firm's 8-hour capacity indicated an exceptionally low utilization of capital. Important product markets in agribusiness and public highway construction were very depressed during this period.

It may be that the finding of constant returns to scale was the result of low levels of production rather than the technical relationships between inputs and outputs observable during normal levels of production. Likewise, the conclusion that constant marginal costs yield perfect price elasticity of demand for raw materials may not be the case. A time series of the post and pole sector would help clarify the price elasticity of demand for small-diameter wood products.

MARKET SUPPLY OF POST AND POLE PRODUCTS

The production function and the associated marginal cost curve for the representative post and pole firm shown in figure 5b lead to some logical inferences about the aggregate short-run supply function. The perfectly elastic MC function for the competitive firm suggests a perfectly elastic short-run supply function. Of course, the short-run supply function assumes the number of firms, factor prices, and technology to be constant.

As was the case in estimating raw material demand, producer responses were used to develop an alternate measure of supply. Producers indicated how much they would change production if there were a 10 percent increase in product prices, given production costs did not change. The aggregate response was an increase in volume of 646,823 ft^3, or a 19.72 percent change. This translates to an estimate of price elasticity of supply of 1.97 since elasticity is simply the percentage change in quantity demanded divided by the percentage change in price. Thus, both approaches yield consistent results that indicate the supply of post and pole products is price elastic.

CONCLUSIONS

The results of this study suggest a variety of means for increasing the utilization of small-diameter lodgepole pine.

First, judging by the production function estimated by this study, constant returns to scale do not seem to limit firm size. Rather, the individual firm and the post and pole sector as a whole are limited by the size or extent of the market for their products. The largest firms ship more of their products out of State, both in absolute and in relative terms, than do the smaller firms. Further, the out-of-State markets are characterized by different distribution channels than the in-State market. The top quartile of producers primarily sells to wholesalers rather than end users, as is the case with smaller firms. It is also of note that about 1 out of every 5 ft^3 of post and pole products manufactured in the State is shipped to the California/Nevada area.

Second, the most significant external influence on demand is the economic health of agribusiness. The short-term prospects for many components of agriculture are affected by changes in the value of the U.S. dollar relative to foreign currencies and to the structure of production costs of American goods relative to those of other nations. The long-term outlook for American agriculture is likely to be brighter if densely populated countries (particularly in the Pacific Rim) acquire more wealth and increase their demand for agricultural products.

The problems of freight rates and location will continue to plague Montana producers. This will be particularly true of lower priced products. A rise in freight costs per cubic foot increases the price of low cost products at destination relative to the delivered price of higher priced products. Thus, firms with wood preservative facilities may be better candidates for expansion than those without that capability. Treated products command higher prices than untreated products.

Third, the results of this study indicate that the National Forests are not the primary source of raw materials for posts and poles. Even though 60 percent of Montana's total forest lands available for timber harvesting are in Forest Service ownership, post and pole producers secured only 35 percent of their raw materials from this source. The largest producers are the least reliant on the National Forests, which suggests that their suppliers operate in a different arena than those who sell to smaller firms.

Fourth, the analysis of raw material demand and product supply suggests that purchases and production levels are both quite sensitive to price. Demand for raw materials is price elastic, as is product supply.

A wide variety of raw material prices and products prices were observed within the post and pole sector. The main reason for this variation in prices is the myriad sizes of products available. By means of regression analysis, price equations were estimated for the sector as a whole. These equations suggest that the value of the raw materials and products is highly uniform, given allowances for size variation and/or other product characteristics such as treatment with preservative. This uniformity in price indicates that Montana is a component of some larger market area. Because market areas can be distinguished as regions with uniform price, it appears that submarkets do not exist within the State. The raw material and product price equations provide good estimations because of the geographic uniformity of value.

In summary, new information has been provided about post and pole manufacturing in Montana. The nature of the firms, mix of products, competitiveness of markets, channels of distribution, structure of costs, and prices of raw materials and products have been described in detail. This sector is often overlooked because it operates at the periphery of the larger lumber and plywood industry. Nevertheless, it represents an important and efficient utilization of small-diameter timber for the production of wood products.

REFERENCES

Baker, F. S. 1950. Principles of silviculture. New York: McGraw-Hill. 414 p.

Benson, Robert E. 1984. [Personal communication]. Missoula, MT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forestry Sciences Laboratory.

Friedman, Milton. 1976. Price theory. Chicago: Aldine Publishing Co. 357 p.

Green, Alan W.; O'Brien, R. A.; Schaefer, J. C. 1986. Montana's forests. Resour. Bull. INT-38. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 70 p.

Keegan, Charles E., III. 1980. Montana's forest products industry: a descriptive analysis. Missoula, MT: University of Montana, Bureau of Business and Economic Research. 107 p.

Koutsoyiannis, A. 1977. Theory of econometrics. 2d ed. London: Macmillan. 681 p.

Silberberg, Eugene. 1978. The structure of economics. New York: McGraw-Hill. 543 p.

Walters, A. A. 1963. Production and cost functions: an econometric survey. Econometrica. 31: 1-66.

APPENDIX A: DEMONSTRATION OF THE USE OF RAW MATERIAL AND PRODUCT PRICE EQUATIONS

Problem: Estimate cost and price for an 8-foot-long post with 6-inch small-end diameter (top) converted into a fully treated decorative fencepost with holes.

Raw Material Cost Equation—

$$P_1 = 0.1799 + 0.0027\,D^2L + 0.00001162\,e^L$$

where:

P_1 = cutters' price per piece delivered to yard
D = diameter in inches
L = length in feet
e^L = the exponential function 2.718282.

$P = 0.1799 + 0.0027(36)(8) + 0.00001162(2.718282)(8) = \$0.99$ per post

Finished Product Price Equation—

$$P_4 = 0.1009 + 0.9643\,H + 0.0128\,D^2L + 0.1165\,SAT$$

where:

P_4 = cutters' price per piece delivered to yard
D = diameter in inches
L = length in feet
H = a "dummy" variable set to a value of 1 when holes are drilled or set to 0 when holes not drilled
SAT = estimate of surface area treated $(\pi)(D/12)(L)$.

$P_4 = 0.1009 + 0.9643(1) + 0.0128(36)(8) + 0.1165\,(\pi)(6/12)(8) = \$6.21$

APPENDIX B: EQUIPMENT SUMMARY

The 21 firms used in the study indicated that they used the following equipment in their businesses:

Equipment	Number of firms
Pointer	20
Pole shaver (peeler)	19
Butt vats	17
Full-length vats	14
Cutoff saws	13
Mortising drill	11
Doweler	9
Pressure cylinder	4
Forklifts	4
Boilers	3
Kilns	2
Loaders	2

Jackson, David H.; Jackson, Kathleen O. 1989. Montana's post and pole industry: an economic analysis of production and markets. Res. Pap. INT-398. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 14 p.

Montana's post and pole manufacturing industry is described in terms of the products manufactured, size of firms, degree of competition, markets, raw material costs, and product prices. Estimates are presented for demand for raw material and the supply of finished products.

KEYWORDS: roundwood products, timber utilization, forest economics, forest industries, small tree utilization

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department of
Agriculture

Forest Service

**Intermountain
Research Station**

Research Paper
INT-399

March 1989

Differential Susceptibility of Ponderosa Pine to the Gouty Pitch Midge (*Cecidomyia piniinopis*)

R. J. Hoff

THE AUTHOR

R. J. HOFF is principal plant geneticist with the Intermountain Research Station's Forestry Sciences Laboratory in Moscow, ID. He received a B.A. degree in biology from Western Washington State University and a Ph.D. degree in botany from Washington State University.

RESEARCH SUMMARY

In 1985, 14-year-old ponderosa pine in a provenance test in northern Idaho were severely damaged by the gouty pitch midge. Dead or dying tips varied from 0 to 85 percent for individual trees, and 0 to 17 percent for provenances. The most resistant provenances came from seed collected in northernmost Idaho and northwestern Montana where the midge is more abundant than in the southern portions of the study area, comprising central Washington, the northern slopes of the Salmon River, and the Bitterroot River of Montana. Resistance to the midge apparently is an inherited trait influenced by degree of exposure of parent trees.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Differential Susceptibility of Ponderosa Pine to the Gouty Pitch Midge (*Cecidomyia piniinopis*)

R. J. Hoff

INTRODUCTION

In 1985 a provenance test of ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) was severely damaged by the gouty pitch midge (*Cecidomyia piniinopis* Osten Sacken). On many trees a high percentage of the current year's shoots were dead or dying. Several of these trees were dead a few months later.

The gouty pitch midge (GPM) is a native pest of forests of eastern and western North America. In the West the pest is especially injurious to ponderosa pine where the level of infestation becomes high enough to kill trees (Bedard and others in press; Eaton and Yuill 1960). In contrast, outside of damage caused by mortality, Bedard and Ferrell (personal communication) found that growth loss was not related to infestation by GPM. Natural controls such as weather, host resistance, and parasites normally keep it in check (Eaton and Yuill 1960). There is little doubt that the host has defense mechanisms that prevent or limit infestation (Austin and others 1945; Duffield 1985; Hoff 1988). There is little information on how infestation by GPM influences host resistance with respect to elevation and geographic area. Ferrell and others (in press) have reported that in California populations of ponderosa pine from the northern Sierra Nevada and southern Cascades had relatively high levels of resistance to GPM—susceptibility increased with decreasing latitude.

The purpose of this paper is to document the susceptibility of provenances of ponderosa pine from the Northern Rockies of the United States to gouty pitch midge.

MATERIALS AND METHODS

The study site was a provenance test that was severely damaged by GPM. This plantation was established in 1974 by the Northern Region of the Forest Service at the Lone Mountain Tree Improvement Site 25 miles (40 km) north of Coeur d'Alene, ID (fig. 1). This plantation is one of six that have been established in cooperation with the Inland Empire Tree Improvement Cooperative. The site is flat with only slight undulations at an elevation of 2,488 ft (758 m). The entire 160-acre (65-ha) site is surrounded by naturally regenerated ponderosa pine and lodgepole pine, with a lesser mixture of grand fir, Douglas-fir, and western larch. This natural stand is two-layered; the overstory is composed of mature scattered trees (remnants of harvest) and the lower layer is a pole-sized stand 20 to 30 ft (6 to 9 m) tall. Many of these natural ponderosa pine were infested with GPM.

The seed came from 92 stands (populations) located in northeastern Washington, Idaho north of the Salmon River, and western Montana (fig. 1). Open-pollinated seed were collected from five individuals per stand.

The seedlings were grown at a Forest Service nursery near Coeur d'Alene, ID, in bare-root beds for 2 years, lifted, and planted at the Lone Mountain Tree Improvement Site in April 1974. The experimental design was a randomized complete block with 10 replications (blocks). Four progeny of each stand were planted per replication as a four-tree row plot.

Data were taken by estimating the number of dead or dying (off-color) branch or leader shoots. The range of damaged shoots was determined by sample counts of damaged shoots throughout the test on several trees. From this inspection a scoring system was developed to apply to all trees. Then the amount of infestation for each tree was estimated and placed in one of the following classes:

0 = 0	infested branch or leader shoots, mean = 0
1 = <5	infested branch or leader shoots, mean = 2.5
2 = 6-32	infested branch or leader shoots, mean = 19
3 = 33-67	infested branch or leader shoots, mean = 50
4 = 68-100	infested branch or leader shoots, mean = 84

Tree height varied from 3.6 ft (1.1 m) to 30.0 ft (7.0 m), and so to determine the proportion of shoots damaged on a tree basis, a regression of the total number of tips per tree (healthy and damaged) by height was determined. A random sample of 224 trees (6 percent of total trees) was selected to develop the following regression formula:

estimated percent damage = number damaged shoots/TT where $TT = a + bx$, and TT = total shoots, x = tree height, a and b = regression coefficients, number damaged = the mean of the estimated number of damaged shoots.

A goodness-of-fit procedure was used to compare actual shoot damage with estimated shoot damage. Because estimated damage covered a wide range, it was transformed (arcsin $\sqrt{\text{percent}}$ damage) (Steel and Torrie 1960).

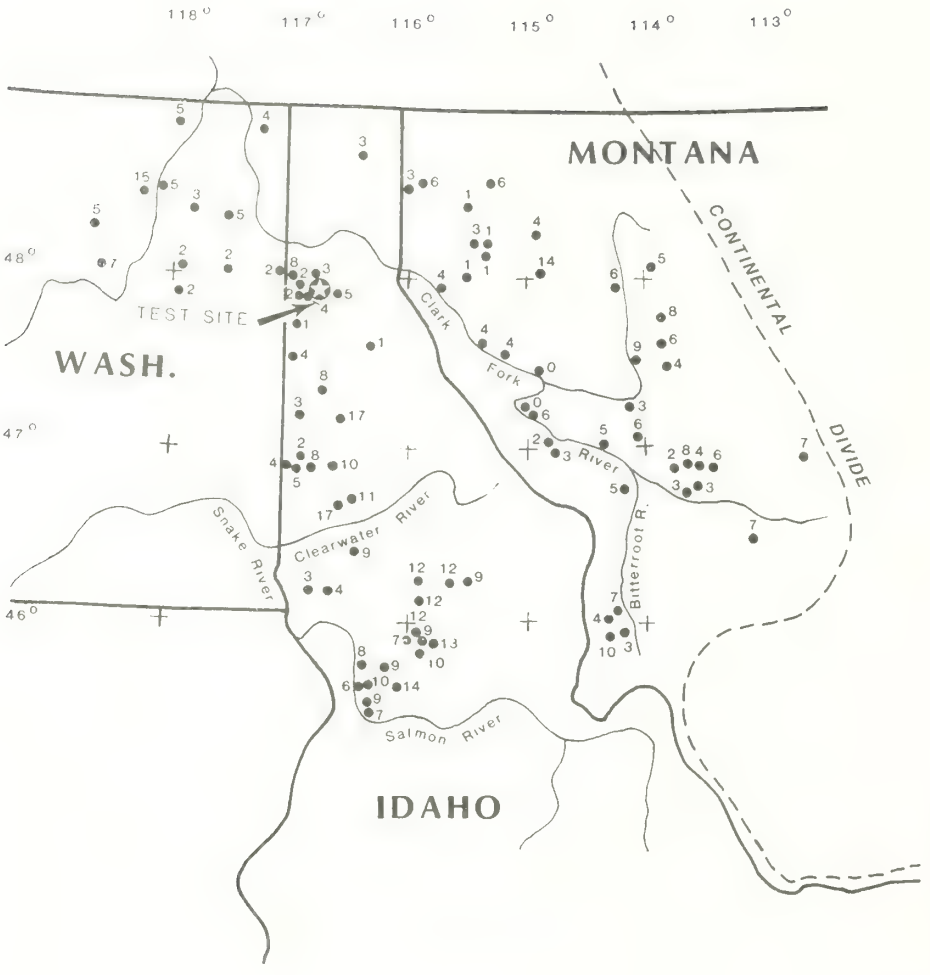


Figure 1—Dots are seed source locations for the ponderosa pine provenance test at Lone Mountain Tree Improvement Site; numbers are the estimated mean percentage of current year's shoots dead or dying due to infestation by gouty pitch midge.

An analysis of variance of the estimated damage was used to determine significant differences among stands. A balanced ANOVA (SAS 1982) was used for variables blocks (replications) and stands. Stepwise multiple regression analyses were used to relate the degree of GPM damage to elevation and geographic location of the seed source. Independent variables included elevation, latitude, longitude, northwest-southeast coordinates, southwest-northeast coordinates, and their squares. The northwest-southeast coordinates equaled latitude x longitude and the southwest-northeast coordinates equaled (1/latitude) x longitude. The geographic variables were nested within two geographic regions: (1) Idaho north of the Salmon River and (2) Montana west of the Continental Divide. A stepwise multiple regression procedure for maximizing R^2 (SAS 1982) was followed.

Predicted percentage of GPM damage for geographic area was computed using the best fit multiple regression equation for a constant elevation. Contour lines (isopleths) separating statistically equal levels of the estimated damage were determined by using the least significant difference formula (Steel and Torrey 1960) at a t-value of 0.2.

RESULTS

The regression of total current shoots per tree (TT) for the sample resulted in regression coefficients of $a = -68.0$, and $b = 22.6$ shoots per foot, $R^2 = 0.69$. The goodness-of-fit procedure yielded a chi-square of 1.38, which was highly significant but probably somewhat underestimated since in the sample 60 percent of the trees were not infested with GPM.

The average level of estimated percent damage by GPM was 6 percent. Individuals varied from 0 to 85 percent, and stands varied from 0 to 17 percent. The frequency of damage classes by individuals is summarized in table 1. Differences among stands were highly significant (table 2).

Regression coefficients for the stepwise multiple regression equation that produced the best fit resulted in an R^2 of 0.46, a mean square of 0.0062 with 9 degrees of freedom, and an error mean square of 0.0008 with 82 degrees of freedom resulting in an F value of 7.7, significant at 1 percent level of significance (table 3).

Midge damage by seed source is shown in figure 1, and predicted values from the multiple regression equation are shown in figure 2. The dotted line represents the average predicted value, and the solid contour lines are derived from $+^1/_2$ lsd from the mean at the 0.2 level of significance.

Table 1—Frequency of gouty pitch midge damage classes on the new shoots of ponderosa pine

Damage class	Number of shoots damaged		Frequency of progeny
	Mean	Class interval	
			Percent
0	0	0	40
1	2.5	<5	22
2	19	6-32	23
3	50	33-67	13
4	84	68-100	2

Table 2—Analysis of variance of the estimated proportion of gouty pitch midge damage on ponderosa pine

Source of variance	df	MS	*F* value
Block	9	0.122	
Stand	91	.073*	3.65
Block X Stand	[1]782	.020	

[1]Reduced due to 37 missing plots.
*Significant at the 1 percent level of probability.

Table 3—Regression coefficients from the best fit stepwise multiple regression equation for damage caused by the gouty pitch midge to ponderosa pine

Factor	*b* value
Intercept	–46.786403
Elevation	–.000003
Northwest	–.006117
Northwest-1	.029054
Southwest-1	109.977010
Latitude	1.363577
Latitude-1	–2.356577
Longitude-1	–1.788316
Southwest[2]	2.639739
Southwest-1[2]	18.317636

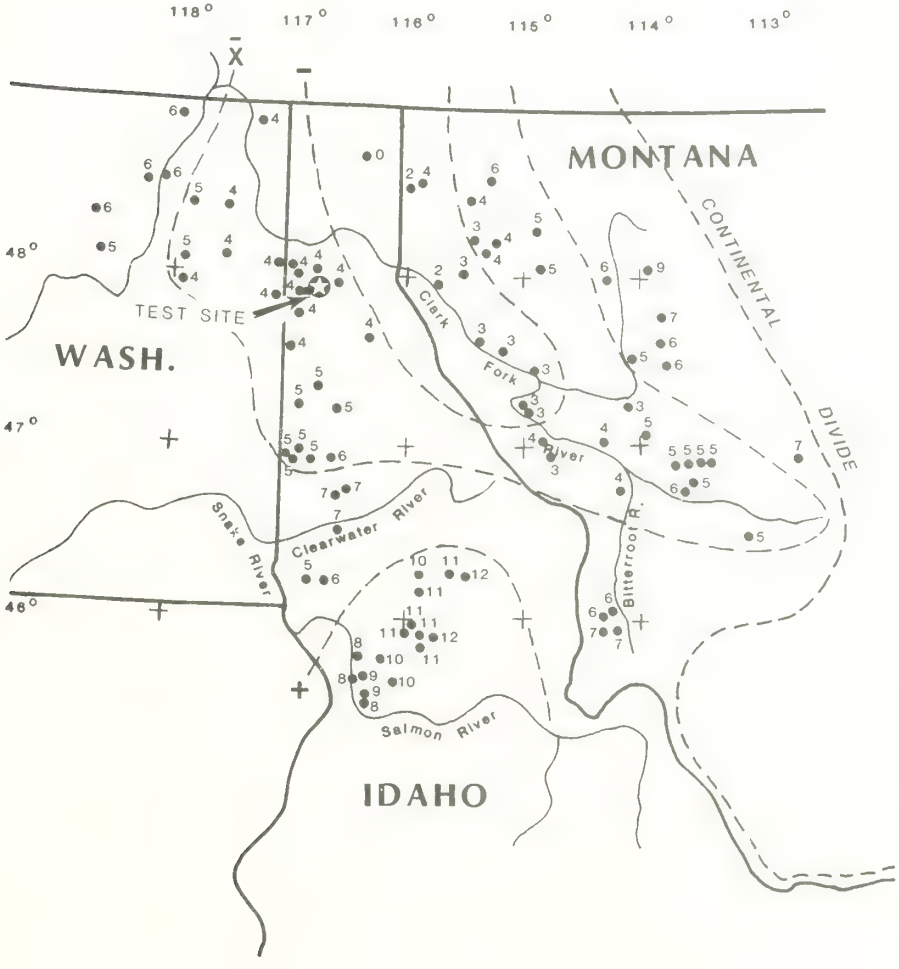


Figure 2—Dots are seed source locations for the ponderosa pine provenance test at Lone Mountain Tree Improvement Site and numbers are predicted levels of damage (percentage) by gouty pitch midge for populations of ponderosa pine. Geographic patterns of variation are shown by isopleths (contour lines). The interval between isopleths equals $^1/_2$ [lsd(0.2)]. Isopleths represent positive or negative deviations from the mean value ($\bar{x}$) of all populations.

DISCUSSION

Although damage due to gouty pitch midge amounted to an average of only 6 percent of the new shoots, differences among stands were statistically significant. The differences were associated with geographic area. The stands with the highest resistance were located in the north-central portion of the collection area, namely in the extreme northern portion of Idaho and adjacent areas of northeastern Washington and northwestern Montana. The areas farther east, west, and south were more susceptible. Also, the most susceptible stands were those that were farthest away from the planting site. These collections came from the area just north of the Salmon River in Idaho.

Little is known about the environmental requirements of GPM. But the insect shows up most frequently in areas that are cool and moist, such as northern Idaho and adjacent areas. This would explain the higher resistance observed in the populations of pine from these areas and conversely would explain the higher susceptibility of populations from the warm-dry portions of the collection area, that is, central Washington and areas just north of the Salmon River of Idaho and in the Bitterroot Valley of Montana.

There is no doubt that the midge can cause damage severe enough to cause mortality, and therefore it is difficult to understand why there would be no growth loss on more moderately infested trees as suggested by Bedard and Ferrell (in press). An epidemic would not have to last long before the amount of mortality would significantly impact stocking. Fortunately, in 1987, the insect appears to be decreasing and the epidemic may have passed.

CONCLUSIONS

The finds of this study emphasize the need to consider resistance to pests when provenence testing. Movement of seed from one area to another without this knowledge could result in unacceptably high levels of damage and mortality in areas reforested with seedlings having little or no resistance to a specific pest.

REFERENCES

Austin, L.; Yuill, J. S.; Brecheen, K. G. 1945. Use of shoot characters in selecting ponderosa pines resistant to resin midge. Ecology. 26: 288-296.

Duffield, J. W. 1985. Inheritance of shoot coatings and their relation to resin midge attack on ponderosa pine. Forest Science. 31: 427-429.

Bedard, W. D.; Ferrell, G. T. [Personal communication]. Growth of ponderosa pine not related to injury caused by gouty pitch midge (Diptera: Cecidomyiidae). Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station.

Bedard, W. D.; Robertson, A. S.; Ferrell, G. T. 1989. Growth loss in sapling ponderosa pine associated with gouty pitch midge-caused injury. In: Ferrel, R. T.; Glover, S. G. Insects affecting reforestation: biology and damage: Proceedings of the IUFRO Working Group on Insects Affecting Reforestation; 1988 July 3-9; Vancouver, BC: 196-205.

Eaton, C. B.; Yuill, J. S. 1960. Gouty pitch midge. For. Pest Leafl. 46. Washington, DC: U.S. Department of Agriculture, Forest Service. 8 p.

Ferrell, R. T.; Bedard, W. D.; Westfall, R. D. 1989. Geographic variation in *Pinus ponderosa* susceptibility to the gouty pitch midge, *Cecidomyia pinniopis*, in the Sierra Nevada and southern Cascade mountains of California. In: Ferrel, R. T.; Glover, S. G. Insects affecting reforestation: biology and damage: Proceedings of the IUFRO Working Group on Insects Affecting Reforestation; 1988 July 3-9; Vancouver, BC: 205-213.

Hoff, R. J. 1988. Resistance of ponderosa pine to the gouty pitch midge *Cecidomyia piniinopis*. Res. Pap. INT-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 3 p.

SAS Institute, Inc. 1982. SAS user's guide: statistics. Cary, NC: SAS Institute, Inc. 584 p.

Steel, R. G. D.; Torrie, J. H. 1960. Principles and procedures of statistics. New York: McGraw-Hill. 481 p.

Hoff, R. J. 1989. Differential susceptibility of ponderosa pine to the gouty pitch midge (*Cecidomyia piniinopis*). Res. Pap. INT-399. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 4 p.

In 1985, 14-year-old ponderosa pine in a provenance test in northern Idaho were severely damaged by the gouty pitch midge. Dead or dying tips varied from 0 to 85 percent for individual trees, and 0 to 17 percent for provenances. The most resistant provenances came from seed collected in northernmost Idaho and northwestern Montana where the midge is more abundant than in the southern portions of the study area, comprising central Washington, the northern slopes of the Salmon River, and the Bitterroot River of Montana. Resistance to the midge apparently is an inherited trait influenced by degree of exposure of parent trees.

KEYWORDS: insect resistance, pest resistance, seed source

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

United States
Department
of Agriculture

Forest Service

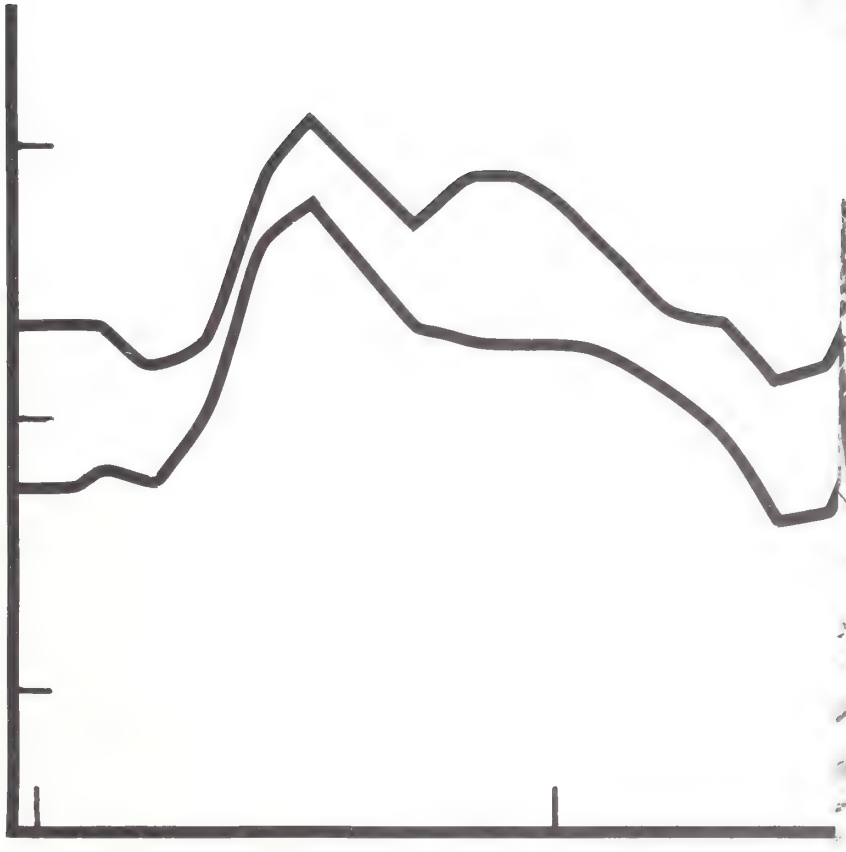
**Intermountain
Research Station**

Research Paper
INT-400

March 1989

Microclimate: an Alternative to Tree Vigor as a Basis for Mountain Pine Beetle Infestations

Dale L. Bartos
Gene D. Amman



AUTHORS

DALE L. BARTOS is an operations research analyst with the Mountain Pine Beetle Population Dynamics research work unit, Ogden, UT. He joined the unit in 1984 and is currently located in Logan, UT. Prior to assuming his current position, he was with the Intermountain Research Station as a member of the aspen ecosystem project for 12 years. He holds B.S. and M.S.degrees from Fort Hays Kansas State University, and a Ph.D. degree in range science from Colorado State University. His principle research interests are in systems modeling and ecological processes.

GENE D. AMMAN is Project Leader of the Mountain Pine Beetle Population Dynamics research work unit. He joined the unit in 1966. Prior to joining the Intermountain Station, he was research entomologist with the Forest Service's Southeastern Forest Experiment Station in Asheville, NC, doing biological control and ecological research on the balsam woolly adelgid. He began his Forest Service career with the Rocky Mountain Forest and Range Experiment Station in Fort Collins, CO, as research assistant on sampling populations and mortality factors of mountain pine beetle and spruce bark beetle. He has B.S. and M.S. degrees from Colorado State University and a Ph.D. degree from the University of Michigan.

RESEARCH SUMMARY

Microclimates of thinned and unthinned stands of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) were monitored and related to mountain pine beetle (*Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]) response. Thinning lodgepole pine stands increased light intensity, wind movement, insolation, and temperature. Temperatures on the south exposure of tree trunks and of soil were significantly higher in thinned than unthinned stands. Light and wind also were higher in the thinned stand. Fewer mountain pine beetles (5 percent of the total) were caught in pheromone-baited traps in a thinned than in an adjacent unthinned stand. Percentage of trees killed by mountain pine beetle was only 2 percent in a thinned stand, compared to 16 percent in an adjacent unthinned stand.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Intermountain Research Station
324 25th Street
Ogden, UT 84401

Microclimate: an Alternative to Tree Vigor as a Basis for Mountain Pine Beetle Infestations

Dale L. Bartos
Gene D. Amman

INTRODUCTION

Temperature is an important factor in the ecology of insects. It affects the physical conditions of habitats and the insects themselves (Wellington 1950). In the case of mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins [Coleoptera: Scolytidae]), observations were made on the effects of extremely high (Patterson 1930) and low temperatures (Somme 1964; Yuill 1941). Between the extremes is an optimum zone of temperature that may be modified by other microclimatic factors (Rudinsky 1962).

Thinning forests causes subtle changes not only in tree physiology (Nebeker and Hodges 1983) but also in incident radiation, temperature, light (Reifsnyder and Lull 1965), and windspeed. These changes brought about by thinning lodgepole pine (LPP) (*Pinus contorta* var. *latifolia* Engelm.) forests have profound effects on MPB activity (Schmitz and others, in press) resulting in reduced tree mortality in thinned stands (McGregor and others 1987).

The silvicultural practice of thinning has been used in the past as a way of increasing tree vigor (Graham and Knight 1965; Keen 1958), which in turn should make the residual trees better able to resist attacks by MPB. The removal of large-diameter lodgepole pine, which are preferred by MPB, can also result in reductions in tree loss during epidemics (McGregor and others 1987). Reduced infestation by MPB occurs immediately following partial cutting of LPP stands (McGregor and others 1987) and before residual trees could express resistance due to increases in growth and vigor as measured by periodic growth ratios and growth efficiency (Amman and others 1988). This phenomenon suggests that factors other than vigor may be responsible for reduced MPB infestation.

Subtle changes in chemistry of residual trees following thinning of stands is one possibility. Biochemical responses detected by the beetles could cause them to avoid trees in thinnings. Nebeker and Hodges (1983) studied the effects of thinning and thinning-related injury to loblolly pine (P. *taeda* L.) by measuring oleoresin exudation pressure, electrical resistance, resin flow rate, total flow, and relative viscosity of resin. They found total flow and relative viscosity were significantly different by month and treatment, with the greatest increase in trees receiving only basal wounding. Matson and others (1987), also studying effects of thinning loblolly pine, found resin flow rates, starch concentration in phloem tissue, relative growth, and bark and phloem thickness were greater in trees in thinned plots than trees in control or fertilized plots, 6 years after treatments were applied. Raffa and Berryman (1982) studied physiological differences between lodgepole pines resistant and susceptible to MPB and associated microorganisms. They found no relationship between resistance and daily rate of resin flow, rate of resin crystallization, monoterpene content, monoterpene composition, or current growth rate. Resistant trees responded to artificial inoculation of fungi vectored by MPB by forming greater quantities of resin than susceptible trees. However, Peterman (1977), in a field test of the fungal inoculation method of distinguishing resistant and nonresistant trees, found the method ineffective. Therefore, we chose to explore the microclimate of the altered stand because (1) microclimate changes immediately following tree removal from the stand and (2) residual trees in the stands were slow to increase growth. The objective of this paper is to present microclimatic differences we observed between thinned and unthinned LPP stands and to discuss beetle behavior in response to these differences.

METHODS AND MATERIALS

The study site is south of Mountain View, WY, on the north slope of the Uinta Mountains in northeastern Utah, at an elevation of 2,865 m. A thinned and an adjacent unthinned stand of LPP, both of which had current beetle infestation,were selected for study of microclimatic differences. An additional thinned and an adjacent unthinned stand of LPP, both of which had no beetle infestation, were selected for study of beetle response to pheromone-baited traps.

Stand Characteristics

Characteristics of the thinned and unthinned LPP stands studied for microclimatic differences were determined through variable plot (10 BAF) cruising. Plots were 50 m apart in a grid pattern in each stand. Trees on the plot were tallied as live or dead by cause of death and were measured for diameter at breast height (d.b.h.). The dominant or codominant tree closest to plot center was

Figure 1—Tower and surrounding instrumentation of 21X as it appeared in the field during the summer of 1986.

measured for height and crown length. Stand density was determined using basal area and number of trees per hectare.

Monitoring Microclimate

An automatic recording device (21X micrologger, Campbell Scientific) was used to measure the microclimatic factors (fig. 1) of temperature, incident solar radiation, windspeed, and wind direction for a 23-day period starting July 19, 1986. This time encompassed the peak MPB flight period, which occurred in the area on August 3, 1986 (Julian day 215) (Schmitz 1987). Equipment limitations dictated we could monitor a full complement of factors on only two trees—one in the thinned and one in the unthinned stand. Both trees were similar in height, crown length, and d.b.h. (about 23 cm). Parameters were recorded every 15 minutes, with averages calculated hourly.

Temperature—Thermocouple psychrometers were connected to the micrologger to measure temperature at the following points on or near the sample trees:

1. At breast height, 1.4 m above ground, on the bark surface and immediately below the surface for both the north and south sides of the trees. The below-bark surface probe was positioned to measure temperature of the tree phloem. Phloem is the substrata in which MPB adults mine and lay eggs and also serves as the food source of developing larvae.
2. In the lower third of the crown on the bark surface, both on the north and south sides of the trees.
3. On the tower (about 3 m above ground) where the micrologger was situated. This sample area was to represent air temperature of the interspace of the stand.

Incident Solar Radiation—LI-COR quantum sensors were used to measure incident solar radiation. These sensors measure photosynthetically active radiation in the 400- to 700-nm waveband. Values reported were for the average energy flux density for the sampled period and are given in units of 1,000 μ einsteins/m^2/s. For both treatments, these solar sensors were placed in three locations: one on the tower, one at breast height on each sample tree, and one in the lower third of the crown. Solar sensors attached to the tree were placed on the north side.

Windspeed—Windspeed sensors were standard 3-cup anemometers, which were connected to the micrologger. Data were reported in units of kilometers per hour. Two sensors were placed in both the thinned and unthinned stands. One sensor was placed on the tower (about 3 m above ground), the other in the lower third of the crown of the sample tree.

Wind Direction—The lightweight wind direction sensor we used is an air-foil vane and a potentiometer, which produced an output that varies proportionally to the wind direction. Output was recorded in degrees and varied between 0 and 360°. This sensor was placed on the tower, which would allow minimum interference from the trees in each of the stands.

Stand Temperatures—Temperatures in the thinned and unthinned stands subjected to microclimate measurements were surveyed to obtain a random sample of temperatures between 10 a.m. and 2 p.m. on August 6, 1986. This period was selected to record maximum solar penetration into the stand. The survey was conducted on 10 transect lines 20 m apart; observations were made at 20-m intervals along these lines. Temperatures of the ground and the north and south sides of the living tree nearest to plot center were obtained with an infrared thermometer (Wahl Digital Heat Spy Model DHS-14). Tree temperatures were taken at breast height. Each survey line passed through both thinned and unthinned stands to avoid any large time lag (approximately 20 minutes used per line) that would have occurred if one stand had been completely surveyed before starting the survey of the other stand.

Beetle Response

Beetle response to thinned and unthinned stands was determined by using pheromone-baited traps in the general vicinity of the microclimate study. Three Lindgren funnel traps were hung in a thinned stand and three in an adjacent unthinned stand. Traps were 100 m apart within stands and 300 m apart between stands. Those stands were approximately 1 km north of the stands where microclimatic observations were made. There were no beetle-infested trees in the two stands at the time of trapping. The traps were baited with the standard MPB lure (Phero Tech Inc.) consisting of *trans*-verbenol, *exo*-brevicomin, and myrcene. Beetles were collected from the traps weekly during a 3-week period, August 15 to September 5, 1985, the summer before microclimate observations were made. Beetles were taken to a laboratory where they were sexed and counted.

Data Analysis

Characteristics and temperatures of thinned and unthinned stands obtained during stand surveys were subjected to analysis of variance to test for significant differences. Statistical analysis of data from the micrologger was not possible because we had only enough equipment to monitor microclimate of one tree in each of the two stands. Therefore, we used a time series analysis system software package for microcomputers to manipulate various combinations of factors to show trends that exist between the thinned and unthinned stands, as well as within the sampled tree. The raw data were plotted, and a smoothing technique was used to reduce some of the inherent variation. We accomplished this smoothing by calculating a moving average of the raw data. These smoothed curves were better able to show consistent trends between similar factors than had previously been observed. Because the version of the program used would accept only 550 values, we used the hour averages to look at the overall trends for the 23 days. More variance was deleted from the curves when a larger time span (49 hours versus 5 hours) was used to obtain the smoothed average. Next, to see if we were masking detail, we used the 15-minute readings and plotted the 5 days that encompassed the peak flight period (Julian day 215). Finally, we plotted averaged smoothed data for the day that peak flight occurred (midnight to midnight).

RESULTS

We looked at the results in terms of stand characteristics, microclimate, and beetle response.

Stand Characteristics

Characteristics of the thinned stand in which microclimate was observed were an average basal area of 22.1 m^2/ ha, a density of 707.8 trees/ha, and an average diameter of 20.2 cm. Dominant and codominant trees averaged 15.1 m in height, with live crown 52 percent of total height. In contrast, the adjacent unthinned stand had a basal area of 37.0 m^2/ha, a density of 1,090.1 trees/ha, and an average diameter of 18.6 cm. Dominant and codominant trees averaged 15.1 m in height, with live crown 53 percent of total height (table 1). Of these stand characteristics, only the stand density measures of basal area and trees per hectare were significantly different between stands ($P < 0.05$).

Stand Microclimate

Temperature (23 Days)—Curves for a 23-day period obtained via smoothing raw data appeared similar between the south and north sides of the sampled tree at breast height in the thinned stand. The average temperature varied between 9 °C at the beginning of the 23 days to a high of approximately 18 °C around August 5, 1986. Both sets of curves show close correlation between the surface and phloem temperatures. However, a slight separation (0.5 °C) was noticed for the south side of the tree.

Similar traces were observed between the thinned and unthinned stand. Subsurface temperatures reflect what occurs on the bark surface but with slightly less magnitude. The phloem curve for the south side in the thinned stand was consistently 1 to 2 °C higher than the phloem curve in the unthinned stand (fig. 2A), while the surface temperature on the south side in the thinned stand (fig. 2B) responded with a 1 to 3 °C greater difference from that in the unthinned stand.

Less difference was observed between the thinned and unthinned stands when comparisons were made on the north side of the sampled trees. Traces of the curves on the north side were similar to those on the south side. However, as expected, the south side was consistently 3 to 4 °C higher. On the north side, curves for the phloem temperature mimicked the surface temperature, and a difference of less than 0.5 °C between the thinned and unthinned stand was observed.

Temperature (5 Days)—Smoothing over a 5-day period was done to express more detail for any one 24-hour period. This information was partially masked when smoothing was done for the full 23 days. Initially, we looked at pairs of curves showing within-tree differences at breast height in both treatments. Similar responses were observed, and figure 3 shows the various combinations. Over a 24-hour period, there is a reversal in dominance of the two temperature curves. From early afternoon through late evening, surface temperature is warmer than phloem temperature, but for the rest of the period it is just the opposite. These trends are consistent from day to day over the 5 days. At the point of maximum separation, there is <0.5 °C difference. We see much more separation in the averaged temperature curves (fig. 4) when we make comparisons between the same sample points for the two treatments. This information is an elaboration of the previous figure 2B. The thinned stand always had the higher temperature. The difference ranged from 2 to 3.5 °C, and the biggest difference occurred during the hottest part of the day.

Table 1—Some average characteristics of the thinned and unthinned stands monitored for microclimatic differences (includes trees 12.7 cm and larger d.b.h.) in northern Utah

Plot[1]	Lodgepole pine per hectare			Basal area	Diameter at breast height		Dominant/ codominant height	Crown length, percentage of total height
	Live	Dead	Killed by MPB		Live	Dead		
	No.		Percent	m^2/ha	cm		Meters	Percent
				Thinned				
1	426.3	0.0	0.0	20.7	24.4	—	13.7	44
2	526.1	.0	.0	11.5	17.0	—	14.6	38
3	805.7	.0	.0	20.7	17.5	—	13.7	69
4	812.0	.0	.0	20.7	17.9	—	14.6	52
5	888.6	70.9	7.4	20.7	17.3	20.6	15.5	51
6	744.3	.0	.0	23.0	19.9	—	14.3	38
7	670.4	70.9	9.6	23.0	20.5	20.3	14.6	67
8	641.2	.0	.0	25.3	22.1	—	17.4	60
9	901.4	.0	.0	32.1	21.3	—	17.7	53
10	519.9	.0	.0	23.0	23.6	—	14.6	52
Average	693.6	14.2	2.0	22.1	[2]19.8	[2]20.5	15.1	52
				Unthinned				
1	0.0	343.0	100.0	20.7	—	27.4	14.3	68
2	.0	536.7	100.0	29.8	—	25.9	15.2	80
3	557.2	316.5	36.2	34.4	19.3	25.4	14.0	52
4	467.3	158.1	25.3	25.3	22.6	23.4	15.9	35
5	1,502.4	.0	.0	39.0	17.3	—	16.5	46
6	1,763.3	.0	.0	56.0	14.2	—	15.2	28
7	1,739.9	.0	.0	43.6	16.3	—	14.3	43
8	1,638.8	135.9	7.7	52.8	18.0	24.9	13.7	42
9	706.5	151.7	17.7	34.4	20.6	26.9	16.5	67
10	784.1	98.8	11.2	34.4	21.1	28.7	15.2	72
Average	916.0	174.1	16.0	37.0	[2]17.6	[2]23.8	15.1	53

[1]Variable plot using a basal area factor 10-angle gauge.
[2]Weighted averages.

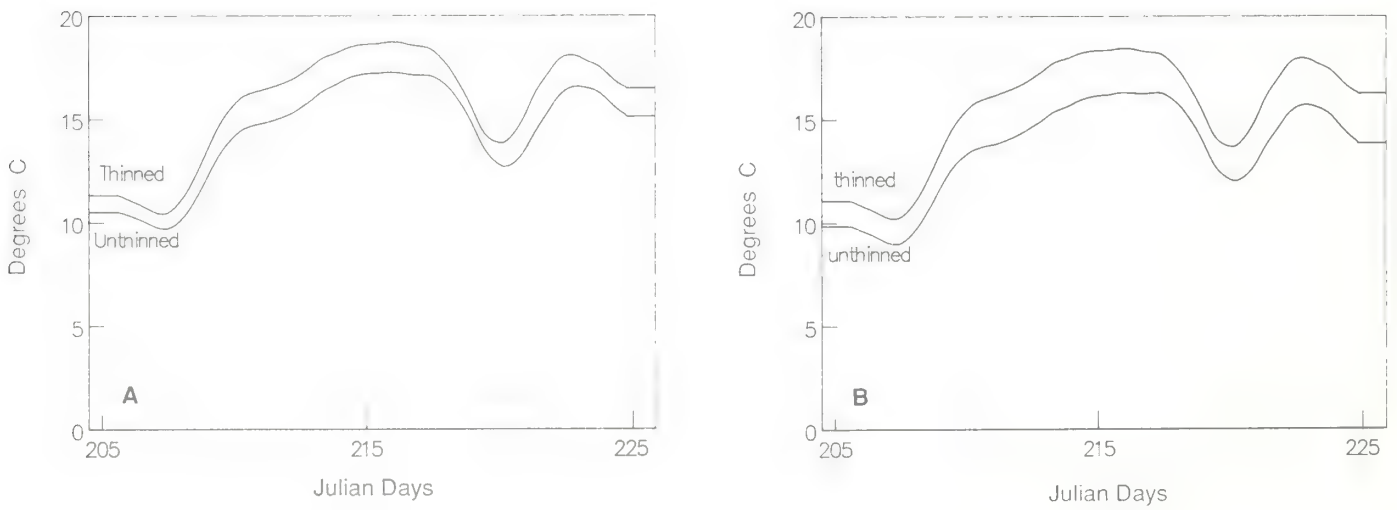


Figure 2—Smoothed curves for a 23-day period contrasting phloem (A) and bark surface (B) temperatures on the south side of two lodgepole pine trees between a thinned and unthinned stand.

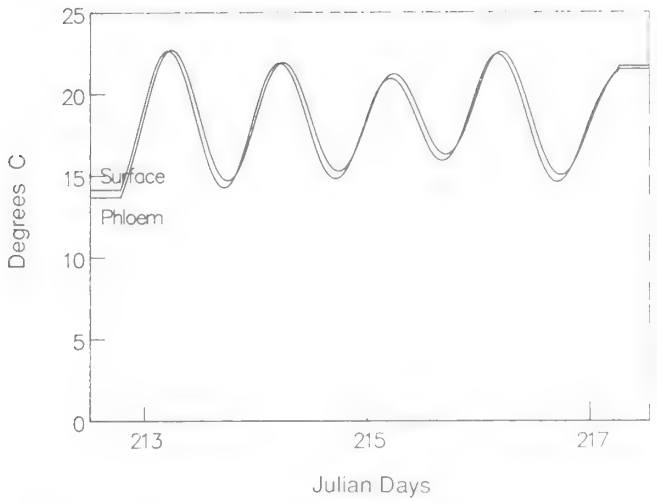


Figure 3—Smoothed curves for a 5-day period contrasting phloem and bark surface temperatures on the south side of a lodgepole pine tree in a thinned stand.

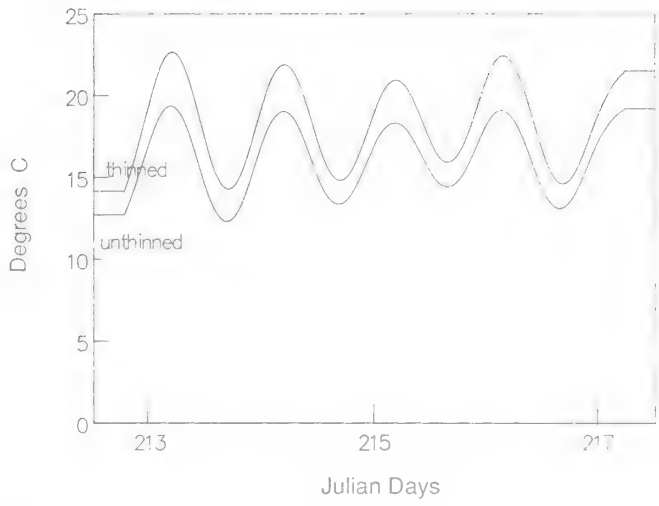


Figure 4—Smoothed curves for a 5-day period contrasting bark surface temperatures on the south side of two lodgepole pine trees between a thinned and unthinned stand.

Temperature (1 Day)—More details are shown when smoothing is done over a 24-hour period. Three typical curves (fig. 5) are shown for temperatures recorded on the north side of the sample trees at breast height. First, we see a reversal in dominance between surface and phloem temperatures both in the thinned stand (fig. 5A) and the unthinned stand (fig. 5B). Magnitude varies between 0 and 7 °C. After sunrise, there is a reversal in the temperature curves, with the phloem temperature higher than the surface temperature. The surface heat buildup accelerates, and by afternoon surface temperature again becomes dominant and remains so until the following morning.

Taking this comparison further, we contrasted the phloem temperature curves for the thinned and unthinned stands (fig. 5C). During late afternoon, there was a peak difference of 8 °C, while during the remainder of the day the two smoothed curves are quite similar. The thinned stand had more heat building up in the phloem than did the unthinned stand.

Solar (23 days)—Incident solar radiation is a measure of the amount of sunlight that strikes the tree surface or forest floor and was expected to be strongly correlated with temperature recorded for various points on or near the sampled trees.

The hourly averages for incoming solar radiation were smoothed to show the daily solar curve for the 23 days. Marked differences in solar radiation were observed between the thinned and unthinned stand at breast height (fig. 6A), while not so striking a difference was shown for the sensors placed on the towers (fig. 6B). It may be hard to interpret trends seen here, particularly those at breast height, because sensors placed on the trees were influenced by occasional shade from various parts of the sample tree. Therefore, the tower sensors were included to serve as a reference for incoming solar radiation.

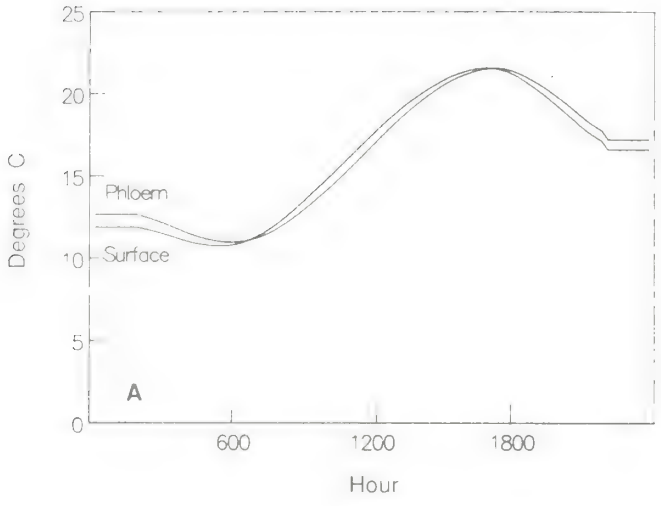
The spread in the values obtained on the trees at breast height was greater than the values obtained from the tower. Therefore, it is assumed that shading is playing a part in the measurement of the factors in figure 6A.

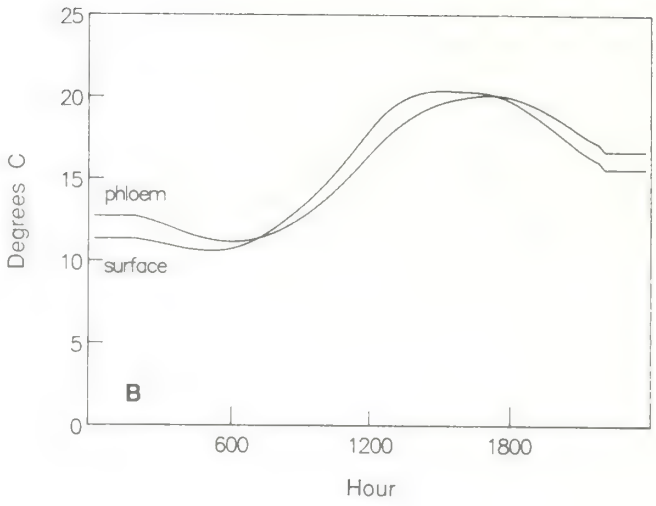
Solar (5 Days)—The daily solar radiation curves smoothed over a 5-day period more explicitly showed the separation we observed earlier (fig. 6A and 6B). Less separation was observed in the two smoothed curves at breast height near the sampled trees when compared to the amount of sunlight striking the sensors on the instrument towers. These differences reflect, in part, placement of the sensors in the stands. Those sensors in the interspaces (on the towers) are probably more representative of measured incident solar radiation within the stands.

Windspeed (23 days)—Windspeed was not smoothed as much as the previously mentioned factors. This allowed some of the variance to remain in the data to more clearly show trends. During a 24-hour period, windspeed as measured on the tower varied between 1.6 and 5.6 km/h (fig. 7). The thinned stand had higher windspeed than the unthinned stand. The average (or overall) difference was only about 1.6 km/h. However, during the period of most MPB flight, between 4 and 6 p.m. (Rasmussen 1974), the difference was consistently 3.2 or more km/h.

Most wind movement occurred at the tower in the thinned stand, while the least movement was within the crown in the unthinned stand. Windspeed varied between 1.6 and 4.8 km/h (fig. 8).

Windspeed (5 Days)—Consistency resulted between the thinned and unthinned smoothed curves (fig. 9) for windspeed on the instrument tower. This set of curves was very uniform for the 5 days. However, smoothed averages for the difference between the two curves varied from 1.0 to 1.6 km/h.





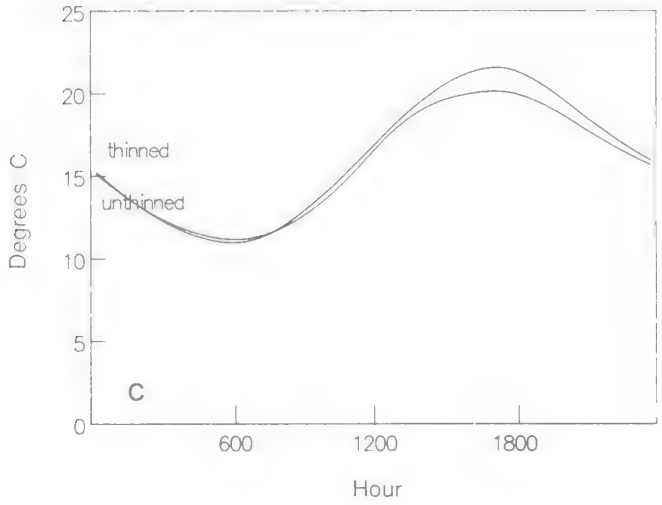
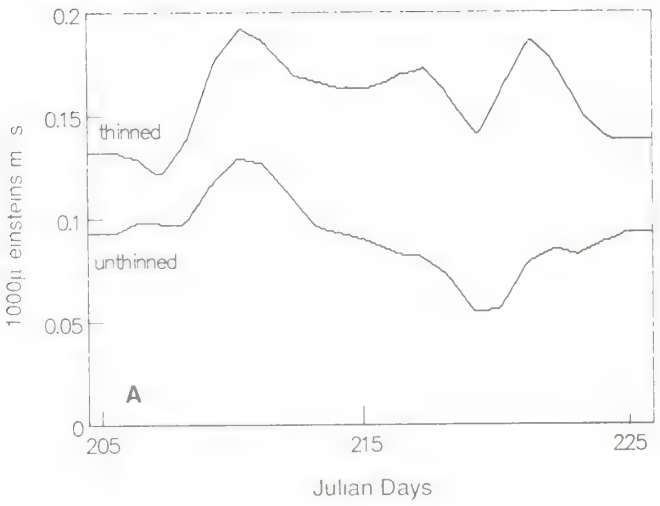


Figure 5—Smoothed curves for a 24-hour period (August 3, 1986). Temperatures at breast height on the north side of the tree are contrasted between (A) bark surface and phloem-thinned; (B) bark surface and phloem-unthinned; and (C) thinned and unthinned phloem.



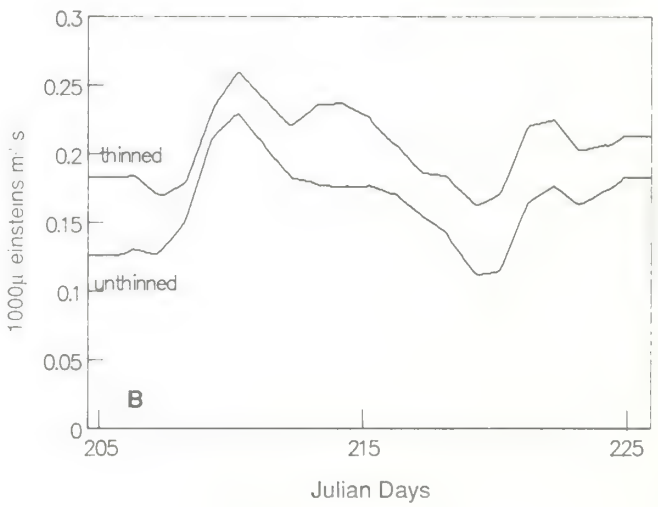


Figure 6—Smoothed curves for a 23-day period contrasting breast height (A) and tower (B) solar radiation between a thinned and unthinned lodgepole pine stand.

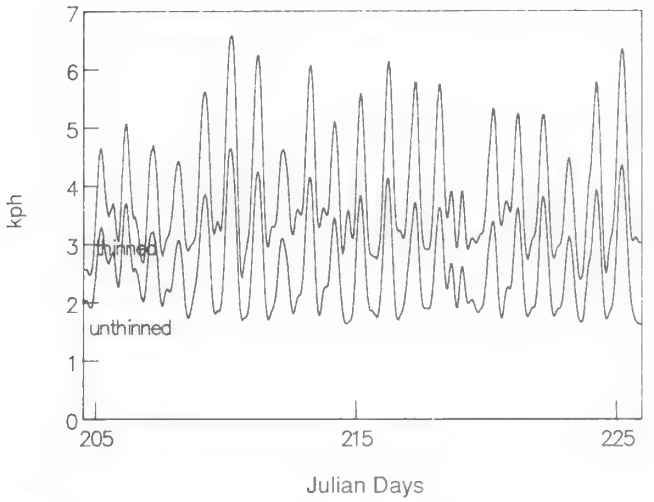


Figure 7—Smoothed curves for a 23-day period contrasting windspeed on the instrument tower between a thinned and unthinned lodgepole pine stand.

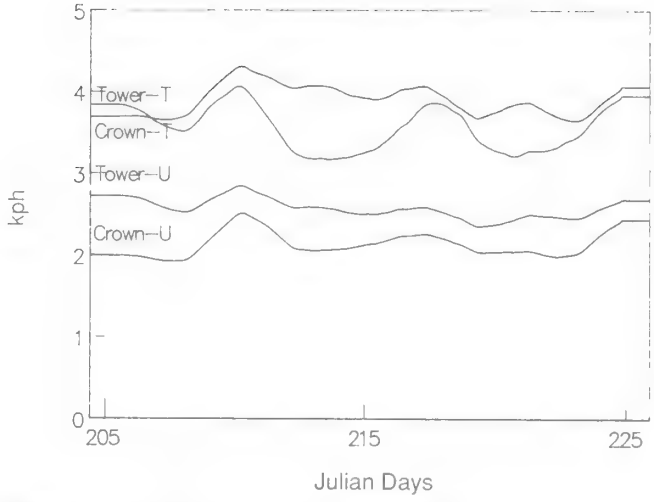


Figure 8—Smoothed curves for a 23-day period contrasting windspeed on the instrument tower and in the crown between a thinned and unthinned lodgepole pine stand.

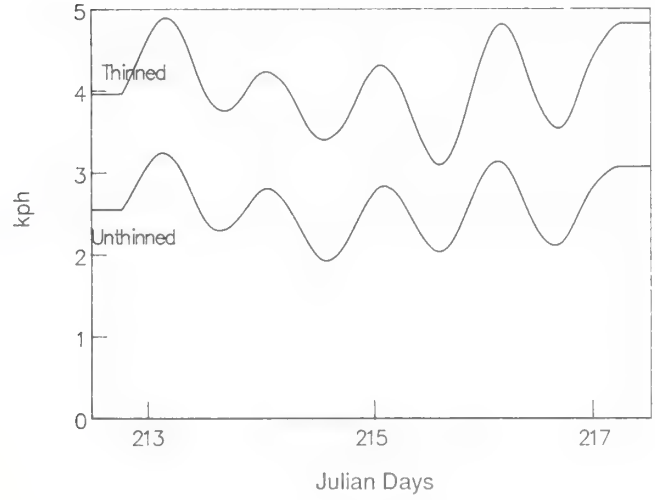


Figure 9—Smoothed curves for a 5-day period contrasting windspeed on the instrument tower between a thinned and unthinned lodgepole pine stand.

Wind Direction (23 Days)—Wind direction was measured on the instrument tower and was obtained mainly for reference purposes. Wind direction varied between 200° and 250°, indicating the average wind direction is from the south to southwest. Also, there was no major difference in direction between the two stands.

Wind Direction (5 Days)—The average wind direction for the 5 days varied between 130° and 250° compared to between 200° and 250° for the 23-day period. The larger range in wind direction for the 5 days shows that some detail is being lost when smoothing techniques are used over longer periods. As in the 23-day period, no major difference in wind direction occurred between the thinned and unthinned stands.

Stand Temperatures—Temperatures of the ground and south sides of trees were significantly higher ($P < 0.05$) in thinned than unthinned stands (ground temperature: thinned $\bar{x}$ = 30.8 °C; unthinned $\bar{x}$ = 26.0 °C) and south side at breast height (thinned $\bar{x}$ = 26.6 °C; unthinned $\bar{x}$ = 24.3 °C). North sides of trees were not significantly different (thinned $\bar{x}$ = 24.2 °C; unthinned $\bar{x}$ = 23.5 °C) (table 2).

Beetle Response

The number of MPB caught in pheromone-baited traps in a thinned stand was only about 5 percent of the total caught in both thinned and unthinned stands. These stands were 1 km from stands where microclimate measures were made. The average numbers of beetles caught per trap were: thinned $\bar{x}$ = 8.7; unthinned $\bar{x}$ = 159.3. Most trapped beetles were females, with a higher percentage being caught in thinned than unthinned stands (thinned = 88.5 percent female; unthinned = 81.2 percent female) (table 3). Stands in which microclimate measures were made had 14.2 trees/ha (2.0 percent) killed by MPB in the thinned stands compared to 174.1 trees/ha (16.0 percent) killed in the unthinned stand.

Table 2—Tree and soil temperatures (°C) in thinned and unthinned lodgepole pine stands obtained by infrared thermometer, August 13, 1985, in northern Utah

		Stand condition							
		Thinned				Unthinned			
Characteristic	Number[1]	Min.	Max.	Mean[2]	Sd	Min.	Max.	Mean	Sd
Soil	50	16	58	30.8a	10.5	14	45	26.0b	6.8
Tree north side	50	13	31	24.2a	3.8	17	30	23.5a	3.1
Tree south side	50	15	45	26.6a	5.6	17	33	24.3b	3.8

[1]Number of observations in each stand.
[2]Means in rows followed by different letters significantly different ($P<0.05$).

Table 3—Numbers of mountain pine beetles caught August 21 to September 5, 1985, in Lindgren traps baited with mountain pine beetle lure and placed in thinned and unthinned lodgepole pine stands in northern Utah

	Males		Females		Total	
Trap No.	No.	Percent	No.	Percent	No.	Percent
			Thinned			
1	0	0.0	3	100.0	3	
2	1	25.0	3	75.0	4	
3	2	10.5	17	89.5	19	
Total	3	11.5	23	88.5	26	5.2
			Unthinned			
1	34	18.1	154	81.9	188	
2	41	19.5	169	80.5	210	
3	15	18.8	65	81.2	80	
Total	90	18.8	388	81.2	478	94.8

DISCUSSION

Our discussion centers on the three areas outlined in the Results section.

Stand Characteristics

The principal difference between the thinned and unthinned stands used in this microclimatic study was the two measures of density. Basal area was 14.9 m^2/ha and numbers of trees 382.3/ha less in the thinned than in the unthinned stand. The average diameters of trees in both thinned and unthinned stands did not differ significantly. The difference in density appears to be responsible for the differences in microclimate in the two stands.

Stand Microclimate

Microclimatic observations showed consistent differences between the thinned and unthinned stands. Thinning lodgepole pine stands results in increased light intensity, wind movement, insolation, and temperature. These factors, either separately or in various combinations, appear to affect MPB activity. The differences observed between thinned and unthinned stands are sometimes quite subtle. However, even minor changes in microclimate could have profound effects on MPB.

The higher temperatures on south sides of trees in thinned stands could be a deterrent to MPB landing and boring into the bark. In our study, south-side temperatures between 10 a.m. and 2 p.m. averaged 2.3 °C higher than those on north sides, with the maximum temperature 12 °C higher in the thinned than unthinned stand. Powell (1967) reported subcortical temperatures were occasionally 35 °C or higher on south sides. Beetles emerge at a greater rate from south than north sides of trees (Safranyik and Jahren 1970). North-side temperatures in thinnings in our study would not have been a deterrent to beetle infestation and offer more favorable physical environment than south-side temperatures for attacking MPB. Beetle attack densities are higher on north sides (Reid 1963; Shepherd 1965), and when trees are strip-attacked, the attacks usually occur on north and east sides (Mitchell and others 1983).

The effect of temperature could be more subtle than a direct inhospitable physical environment on south sides of trees. Mountain pine beetles may have evolved behavior to avoid situations where their brood are not likely to survive. In thinned stands, where tree temperatures are a few degrees above those of trees in unthinned stands, MPB may proceed too far in their development before winter, thus entering winter in stages that are susceptible to freezing—for example, the pupal stage as observed by Reid (1963) and Amman (1973).

Another way that MPB behavior may be affected by thinning is through the disruption of the pheromone communication system. More sunlight penetrated the canopy in the thinned than unthinned stands, resulting in significantly higher soil temperatures. The increased soil temperatures, which averaged 4.8 °C higher in the thinned than in the unthinned stand in this study, increase convection currents (Rosenberg and others 1983) and air turbulence that could disrupt pheromone plumes and resultant MPB communication. In addition, windspeed is greater in thinned than unthinned stands, thus possibly further complicating pheromone communications by MPB. Beetle response to pheromones is more predictable at windspeeds under 5 km/h, but a few beetles flew at 7.5 km/h (Gray and others 1972). Twice as many males as females flew at windspeeds in excess of 4 km/h.

In dense stands sunlight is absorbed by the upper levels of the tree canopy that in turn heats the surrounding air, creating instability in the air within the upper canopy. This creates an inversion in the stem zone that is characterized by more stable air (Chapman 1967; Fares and others 1980). Inversions tend to be more pronounced in dense stands than in sparse ones (Fares and others 1980; Fritschen 1984). Aerosol movement below a dense canopy on a sunny day is trapped beneath the canopy until it flows to a point where the canopy is less dense or has an opening (Fares and others 1980). Solar energy penetrating through canopy openings to the forest floor heats the ground and adjacent air, which becomes buoyant and rises through the canopy opening, carrying the aerosol with it (Fares and others 1980). The aerosol or pheromone plume would be torn apart in the faster, more turbulent air currents above the canopy. Therefore, when MPB infest a tree in a recently thinned stand, canopy density usually is insufficient to trap the pheromone and move it horizontally to attract other beetles. Rather, the pheromone rises through the canopy on convection currents and is dispersed above the canopy. Schmitz and others (in press) concluded that most MPB fly in the bole area beneath the canopy where the pheromone communication system would be most effective.

When MPB do infest a tree in a thinned stand of lodgepole pine, usually only the single tree is infested, and occasionally a nearby tree when spacing is not maintained. The openness of the stand causes convection currents created by solar insolation to transport the pheromone plume around infested trees vertically out of the stand rather than horizontally. Thus, the infestation of other trees would be dependent on the degree of thinning. Older thinnings will probably provide a suitable environment for MPB. As the thinned stand matures, shade will increase and light and temperature decrease because of increased crown size, development of a shrub and young tree layer, and failure of limbs to prune. Therefore, stand microclimate will likely become conducive to beetle infestation before tree competition becomes severe.

Beetle Response

Mountain pine beetle response to baited funnel traps was much less in an uninfested thinned than in an uninfested unthinned stand located 1 km from stands that contained weather instruments, with only about 5 percent of total beetles caught in the thinned stand. Beetles may have passed through the thinned stand without detecting a point source of aggregative pheromone. Beetle abundance was also reflected in the percentage of trees killed which was much less (2 percent) in the thinned stand than in the unthinned stand (16 percent) where weather instruments were located. Schmitz and others (in press) caught fewer beetles in passive traps in heavily thinned than in lightly thinned and check stands in Montana, and McGregor and others (1987) found significantly fewer infested trees in heavily thinned than in lightly thinned and check stands. Because air temperatures in thinned and unthinned stands are about the same, beetles may sense the difference in light intensity or the greater air turbulence in thinned stands and avoid the open stand. Light could serve as an integrator of other micrometeorological features such as temperature, humidity, and air turbulence. Shepherd (1966) showed in laboratory studies that MPB increased attempts to fly as light intensity and temperature increased.

Our observations suggest microclimate could play a significant role in MPB behavior in lodgepole pine stands. Infestation risk of managed LPP stands possibly could be assessed by monitoring stand microclimate, specifically light. If microclimate changes are responsible for keeping beetles at low levels or completely out of thinned stands, forest managers could use such information to write stand management prescriptions to minimize beetle infestation. As crown closure begins to occur in partial cut or thinned stands, a favorable microclimate may occur and invite beetle attack, regardless of tree vigor. Additional studies are needed of MPB infestation in thinned stands to determine more definitively microclimatic thresholds of MPB infestation and the association of thresholds with tree vigor levels.

REFERENCES

Amman, G. D. 1973. Population changes of the mountain pine beetle in relation to elevation. Environmental Entomology. 2: 541-547.

Amman, G. D.; McGregor, M. D.; Schmitz, R. F.; Oakes, R. D. 1988. Susceptibility of lodgepole pine to infestation by mountain pine beetles following partial cutting of stands. Canadian Journal of Forest Research. 18: 688-695.

Chapman, J. A. 1967. Response behavior of scolytid beetles and odour meteorology. Canadian Entomologist. 99: 1132-1137.

Fares, Y.; Sharpe, P. J. H.; Magnuson, C. E. 1980. Pheromone dispersion in forests. Journal of Theoretical Biology. 84: 335-359.

Fritschen, L. J. 1984. Air circulation in forested areas: Effect on aerial application of materials. In Garner, W. Y.; Harvey, J., eds. Chemical and biological controls in forestry: Proceedings; 1983 March 20-25; Seattle, WA. Amer. Chem. Soc. Symp. Ser. 238. Washington, DC: American Chemical Society: 175-190.

Graham, S. A.; Knight, F. B. 1965. Principles of forest entomology. New York: McGraw-Hill. 417 p.

Gray, B.; Billings, R. F.; Gara, R. I.; Johnsey, R. L. 1972. On the emergence and initial flight behavior of the mountain pine beetle, *Dendroctonus ponderosae*, in eastern Washington. Zeitschrift fuer Angewandte Entomologie. 71: 250-259.

Keen, F. P. 1958. Progress in bark beetle control through silviculture in the United States. Tenth Intl. Congr. Entomol. Proc. 4(1956): 171-180.

Matson, P. A.; Hain, F. P.; Mawby, W. 1987. Indices of tree susceptibility to bark beetles vary with silvicultural treatment in a loblolly pine plantation. Forest Ecology and Management. 22: 107-118.

McGregor, M. D.; Amman, G. D.; Schmitz, R. F.; Oakes, R. D. 1987. Partial cutting lodgepole pine stands to reduce losses to the mountain pine beetle. Canadian Journal of Forest Research. 17: 1234-1239.

Mitchell, R. G.; Martin, R. E.; Stuart, J. 1983. Catfaces on lodgepole pine—fire scars or strip kills by the mountain pine beetle? Journal of Forestry. 81: 598-601, 613.

Nebeker, T. E.; Hodges, J. D. 1983. Influence of forestry practices on host-susceptibility to bark beetles. Zeitschrift fuer Angewandte Entomologie. 96: 194-208.

Patterson, J. E. 1930. Control of the mountain pine beetle in lodgepole pine by the use of solar heat. Tech. Bull. 195. Washington, DC: U.S. Department of Agriculture, Forest Service. 20 p.

Peterman, R. L. 1977. An evaluation of the fungal inoculation method of determining the resistance of lodgepole pine to mountain pine beetle (Coleoptera: Scolytidae) attacks. Canadian Entomologist. 109: 443-448.

Powell, J. M. 1967. A study of habitat temperatures of the bark beetle, *Dendroctonus ponderosae* Hopkins, in lodgepole pine. Agricultural Meteorology. 4: 189-201.

Raffa, K. F.; Berryman, A. A. 1982. Physiological differences between lodgepole pines resistant and susceptible to the mountain pine beetle and associated microorganisms. Environmental Entomology. 11: 486-492.

Rasmussen, L. A. 1974. Flight and attack behavior of mountain pine beetles in lodgepole pine of northern Utah and southern Idaho. Res. Note INT-180. Ogden, UT: U.S. Department ofAgriculture, Forest Service, Intermountain Forest and Range Experiment Station. 7 p.

Reid, R. W. 1963. Biology of the mountain pine beetle, *Dendroctonus monticolae* Hopkins, in the east Kootenay region of British Columbia. III. Interaction between the beetle and its host, with emphasis on brood mortality and survival. Canadian Entomologist. 95: 225-238.

Reifsnyder, W. E.; Lull, H. W. 1965. Radiant energy in relation to forests. Tech. Bull. 1344. Washington, DC: U.S. Department of Agriculture, Forest Service. 111 p.

Rosenberg, N. J.; Blad, B. L.; Verma, S. B. 1983. Microclimate: the biological environment. New York: John Wiley & Sons. 315 p.

Rudinsky, J. A. 1962. Ecology of Scolytidae. Review of Applied Entomology. 7: 327-348.

Safranyik, L.; Jahren, R. 1970. Emergence patterns of the mountain pine beetle from lodgepole pine. Canadian Department of Fisheries and Forestry Bi-monthly Research Notes. 26: 11, 19.

Schmitz, Richard F. 1987. [Personal communication] Ogden, UT: U.S. Department of Agriculture, Forest Sevice, Intermountain Research Station, Forestry Sciences Laboratory.

Schmitz, R. F.; McGregor, M. D.; Amman, G. D.; Oakes, R. D. [In press]. Effect of partial cutting treatments of lodgepole pine on the abundance and behavior of flying mountain pine beetles. Canadian Journal of Forest Research.

Shepherd, R. F. 1965. Distribution of attacks by *Dendroctonus ponderosae* Hopk. on *Pinus contorta* Dougl. var. *latifolia* Engelm. Canadian Entomologist. 97: 207-215.

Shepherd, R. F. 1966. Factors influencing the orientation and rates of activity of *Dendroctonus ponderosae* Hopkins (Coleoptera: Scolytidae). Canadian Entomologist. 98: 507-518.

Somme, L. 1964. Effects of glycerol on cold-hardiness in insects. Canadian Journal of Zoology. 42: 87-101.

Wellington, W. G. 1950. Effects of radiation on the temperatures of insectan habitats. Scientific Agriculture. 30: 209-234.

Yuill, J. S. 1941. Cold hardiness of two species of bark beetles in California forests. Journal of Economic Entomology. 34: 702-709.

Bartos, Dale L; Amman, Gene D. 1989. Microclimate: an alternative to tree vigor as a basis for mountain pine beetle infestations. Res. Pap. INT-400. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 10 p.

Thinning lodgepole pine stands increased light intensity, wind movement, insolation, and temperature. Temperatures on the south exposure of tree trunks and of soil were significantly higher in thinned than unthinned stands. Light and wind also were higher in the thinned stand. Fewer mountain pine beetles were caught in pheromone-baited traps in a thinned than in an adjacent unthinned stand. Percentage of trees killed by mountain pine beetle was only 2 percent in a thinned stand compared to 16 percent in an adjacent unthinned stand.

KEYWORDS: *Pinus contorta*, *Dendroctonus ponderosae*, pheromone, lodgepole pine

INTERMOUNTAIN RESEARCH STATION

The Intermountain Research Station provides scientific knowledge and technology to improve management, protection, and use of the forests and rangelands of the Intermountain West. Research is designed to meet the needs of National Forest managers, Federal and State agencies, industry, academic institutions, public and private organizations, and individuals. Results of research are made available through publications, symposia, workshops, training sessions, and personal contacts.

The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

Several Station units conduct research in additional western States, or have missions that are national or international in scope.

Station laboratories are located in:

Boise, Idaho

Bozeman, Montana (in cooperation with Montana State University)

Logan, Utah (in cooperation with Utah State University)

Missoula, Montana (in cooperation with the University of Montana)

Moscow, Idaho (in cooperation with the University of Idaho)

Ogden, Utah

Provo, Utah (in cooperation with Brigham Young University)

Reno, Nevada (in cooperation with the University of Nevada)

USDA policy prohibits discrimination because of race, color, national origin, sex, age, religion, or handicapping condition. Any person who believes he or she has been discriminated against in any USDA-related activity should immediately contact the Secretary of Agriculture, Washington, DC 20250.

☆U.S. GOVERNMENT PRINTING OFFICE: 1989-RI-065-89/3102